RESEARCH MEMORANDUM

A PRELIMINARY INVESTIGATION OF THE USE OF CIRCULATION CONTROL TO INCREASE THE LIFT OF A 45° SWEPTBACK WING BY SUCTION THROUGH TRAILING-EDGE SLOTS

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SUMMARY

An investigation was conducted to determine the effectiveness of circulation control by applying suction through trailing-edge slots on a 45° sweptback wing. Various chordwise extents and depths of slot were investigated with and without deflection of a trailing-edge split flap. The effectiveness of circulation control throughout a large angle-of-attack range was determined with porous area suction applied at the wing leading edge. Limited tests were made with circulation control applied to a two-dimensional airfoil section.

The results indicated that considerable lift increments can be obtained with circulation control applied to a sweptback wing. It was determined that the lift increments could be maintained throughout the angle-of-attack ranges where there was no leading-edge air-flow separation. The lift increment due to circulation control was a function of flow coefficient, extent of slot from the trailing edge, and slot depth.

With circulation control applied to the 45° sweptback wing an increment of lift coefficient of 0.45 could be obtained with a flow coefficient of 0.014, and an increment of lift coefficient of 0.6 could be obtained with a trailing-edge split flap deflected 45° and a flow coefficient of 0.014. Large pitching-moment coefficients were associated with the increases in lift due to circulation control. The two-dimensional airfoil section results are compared with an existing theory of circulation control and a correlation is made between the two- and three-dimensional results.

[redacted]

INTRODUCTION

References 1, 2, 3, and 4 indicate that the lift of an airfoil section can be increased without an increase in angle of attack. According to the theory of Ehlers, reference 1, the variation of lift is obtained by controlling the circulation around an airfoil through the use of a sink near the trailing edge of the upper surface of the airfoil section. Physically, the sink is simulated by suction of air through a finite slot at the trailing edge of the airfoil section. The analysis of Ehlers indicates that the most important variables which determine the magnitude of lift that can be obtained by this method are the quantity of air removed from the potential flow field and the chordwise position of the slot with respect to the trailing edge. Results from reference 2 for two-dimensional airfoil sections substantiate the theory of reference 1 and show that large increases in lift can be obtained on airfoil sections when suction is applied near the trailing edge.

Many current and proposed airplane designs have severe limitations in lift due to the low lift-curve slopes of the sweptback, low-aspect-ratio wings that are being used. Therefore, an investigation was proposed to determine the increment of lift obtainable with circulation control on a 45° sweptback wing. The study was planned to be of a very preliminary nature and was mainly for the purpose of determining whether this method of increasing lift was worthy of more complete investigation on sweptback wings.

The tests on the 45° sweptback wing were specifically directed at providing information on the following general points: (1) Can an increase in lift with this type of circulation control be realized on sweptback wings and, if so, (2) are the trends indicated by Ehlers' theory and two-dimensional results applicable to the sweptback wing? (3) Will circulation control remain effective over a useful range of angles of attack? (4) Does circulation control by suction of air offer a practical means of generating lift on sweptback wings?

The two-dimensional experimental work of reference 2 utilized an NACA 23015 airfoil section which is of greater thickness and different shape than the airfoil sections used on the sweptback wing. Therefore, it was considered necessary to make two-dimensional tests of a thinner, more modern airfoil section, with circulation control applied to provide, (1) an evaluation of Ehlers' theory for the case of thinner airfoil sections, and (2) quantitative information for comparison with the results for the three-dimensional wing.

The investigations of the three-dimensional sweptback wing were conducted in the Ames 40- by 80-foot wind tunnel and the two-dimensional tests were conducted in a 2- by 5-foot wind tunnel. The results of these investigations are reported herein.

COEFFICIENTS AND SYMBOLS

The data are presented in the form of standard NACA coefficients and symbols as defined in the following tabulation:

b wing span, ft

c local chord parallel to plane of symmetry, ft

$\bar{c}$ mean aerodynamic chord, $\dfrac{\int_0^{b/2} c^2 dy}{\int_0^{b/2} c\ dy}$, ft

c' local chord perpendicular to trailing edge, ft

c_l section lift coefficient, evaluated from pressure distribution

c_Q section flow coefficient, $\dfrac{Q}{U_o S'}$

C_D drag coefficient, $\dfrac{\text{drag}}{qS}$

C_L lift coefficient, $\dfrac{\text{lift}}{qS}$

C_m pitching-moment coefficient computed about the quarter-chord point of the mean aerodynamic chord, $\dfrac{\text{pitching moment}}{qS\bar{c}}$

C_p suction pressure coefficient, $\dfrac{p_p - p}{q}$

C_Q total flow coefficient, $\dfrac{Q}{U_o S}$

d depth of trailing-edge suction slot, ft

l chordwise extent of porous area at leading edge measured along surface normal to leading edge, in.

P pressure coefficient, $\dfrac{p_l - p}{q}$

[redacted]

p free-stream static pressure, lb/sq ft

p_l local static pressure, lb/sq ft

p_p plenum chamber total pressure, lb/sq ft

Q volume of air removed per unit time by suction, corrected to standard atmospheric conditions, cu ft/sec

q free-stream dynamic pressure, lb/sq ft

s chordwise dimension of trailing-edge suction slot measured normal to trailing edge, ft

S wing area, sq ft

S' area of model for two-dimensional tests, sq ft

t thickness of felt, in.

U_o free-stream velocity, ft/sec

w_o suction-air velocity, ft/sec

x chordwise coordinate parallel to plane of symmetry, ft

y spanwise coordinate perpendicular to plane of symmetry, ft

α angle of attack, deg

α_u angle of attack not corrected for tunnel-wall interference, deg

δ_f trailing-edge split-flap deflection measured in plane normal to hinge line, deg

ΔC_L lift-coefficient increment due to trailing-edge suction

Δc_l section-lift-coefficient increment due to trailing-edge suction

Subscripts

LE leading edge

TE trailing edge

n component normal to quarter-chord line

p plenum chamber

MODEL AND APPARATUS

Three-Dimensional Model

The geometric characteristics of the model and a photograph of the model mounted in the wind tunnel are shown in figures 1 and 2, respectively. The wing had 45° of sweepback of the quarter-chord line, an aspect ratio of 6.0, and a taper ratio of 0.292. The wing had zero twist and no dihedral. The airfoil sections were symmetrical; the coordinates in planes normal to the wing leading edge are given in table I. The wing had trailing-edge split flaps extending from the fuselage to 0.66 semi-span. The flap chord was 0.25 of the wing chord normal to the quarter-chord line. The hinge line was located at 0.75 of the wing chord normal to the quarter chord.

Surface pressure orifices were located at five spanwise stations on the wing. The spanwise and chordwise locations of the orifices are given in table II.

Trailing-edge slots.- The trailing edge of the wing was constructed as shown in figure 3. The construction was such that along the entire span of the wing a number of slot configurations of variable chordwise extent and depth could be investigated. The various chordwise extents of slot, measured normal to the wing trailing edge, are given in table III. The lower surface was hinged at the 75-percent-chord line (chord normal to quarter-chord line) so that down deflection would permit air to be removed for chordwise slot extents less than 3.0 percent; for these cases, there would have been no finite slot depth unless the lower surface was deflected. The various depths of slot are given in table III. The slot chordwise extent and depth across the span were held within ±15 percent of the values given in table III.

Porous leading edges.- The leading edge was constructed with a porous surface made of a metal mesh backed with variable-thickness wool felt. Figure 3 shows the details of the leading edge. The design method used for the porous leading edge is discussed in references 5 and 6. The metal mesh was 11-percent porous, had 4,225 holes per square inch, and had a thickness of 0.008 inch. The chordwise thickness distribution of the wool felt at various spanwise sections is shown in figure 4; figure 5 gives the pressure-drop characteristics for the metal mesh sheet backed with 1/2-inch-thick wool felt. The chordwise extent of porous surface at five spanwise stations was as follows:

Porous-area extent	Spanwise location, percent				
	24.0	41.2	58.5	75.7	93.0
Percent of chord normal to leading edge	0 to .3	0 to 1.0	0 to 2.2	0 to 4.0	0 to 4.2

Over the area of porous surface where suction was not being applied or during tests where no suction was used, the surfaces were covered with a thin, nonporous cellulose tape.

Suction apparatus.- Two completely separate suction systems were employed; one for the leading-edge area suction and one for the trailing-edge circulation control. The ducting for each system is shown in figure 3. Each system was contained in a separate part of the fuselage which served as a plenum chamber. The leading-edge suction was supplied by means of a centrifugal compressor driven by variable-speed electric motors. Trailing-edge suction was supplied by means of a five-stage axial-flow compressor driven by variable-speed electric motors. Multiple-tube total-pressure rakes were located at the exit of the exhaust ducts to measure the total flow quantities. Static pressure orifices were located in the individual plenum chambers for each system and at several spanwise positions in the leading-edge ducts. Thermocouples were mounted at the exit of each exhaust duct to measure air temperature.

Two-Dimensional Airfoil

The two-dimensional airfoil tested in a 2- by 5-foot wind tunnel had an NACA 64A010 section. A 10.4-percent-chord nose flap was deflected 40° to prevent leading-edge air-flow separation. The airfoil had a 2-foot chord and extended across the 2-foot width of the wind tunnel. Pressure orifices were located on the upper and lower surfaces of the center line of the airfoil. The trailing-edge slots were similar to those for the three-dimensional wing including the variable deflection angle of the lower surface. The two-dimensional airfoil section had a maximum thickness of 10-percent chord compared to the maximum thickness of 10.7-percent chord of the normal section of the sweptback wing.

TESTS

Tests on the 45° sweptback wing were made to determine the magnitude of lift obtainable with circulation control applied by suction of air through slots having various chordwise extents and depths and to

determine the suction flow quantities and pressures necessary to obtain the lift. Three-component force data were obtained at zero sideslip for all slot configurations investigated. For some configurations pressure distributions over the wing were measured. The effect of deflecting partial-span split flaps to 45° and 55° on the increments of lift obtainable with circulation control applied to the entire span of the wing trailing edge was investigated for several configurations of trailing-edge slots. Tests were also made with area suction applied at the wing leading edge to investigate the effect of circulation control over a large range of angle of attack without leading-edge air-flow separation. These latter tests were made only with the slots that indicated the largest increase in lift with circulation control applied.

During the tests the angle of attack and free-stream velocity were held constant as the suction pressure and quantity were varied. This made it possible to obtain the relation between the lift increments and the flow quantity and pressure requirements for each slot configuration. The same procedure was used on the tests with leading-edge area suction applied to obtain the flow quantities and pressure required for leading-edge area suction. The tests were made at Reynolds numbers varying from 3.7×10^{6} to 5.2×10^{6} (based on mean aerodynamic chord of 6.34 feet).

The distribution of suction across the span of the wing was unsatisfactory as was indicated by suction tests with no flow over the model. Very little suction was obtained outboard of 65-percent span at the lower flow quantities and no measurable amount outboard of 75 percent for even the higher flow quantities.

Limited tests were made in the 2- by 5-foot wind tunnel on a few slot configurations at 0° angle of attack. The Reynolds number of the tests was 1.8×10^{6} based on a 2-foot-chord model. The section lift coefficients were determined from measurements of surface pressure distributions on the model.

CORRECTIONS

Tunnel-wall corrections for a straight wing of the same area and span as the sweptback wing were applied to the angle-of-attack and drag-coefficient data. The procedure was followed since an analysis indicated that tunnel-wall corrections were approximately the same for straight and swept wings of the size under consideration. The following increments were added:

$$\Delta\alpha = 0.427\ C_L$$

$$\Delta C_D = 0.0074\ C_L^{2}$$

No corrections were made for strut tares or for strut interference. All flow coefficients were corrected to standard sea-level conditions. The effect of the thrust of the exhaust jets was accounted for in the drag. No corrections were made to the two-dimensional data.

RESULTS AND DISCUSSION

Relatively little research has been done on circulation control effected by means of suction of air through slots at the trailing edge of airfoil sections and no investigations have been made of circulation control applied to a large-scale sweptback wing. Therefore, before entering directly into the results of this investigation, a brief summary based on Ehlers' theory (ref. 1) of the principle of circulation control and the main variables determining its effectiveness will be given. This type of circulation control is a means of producing increases in lift without change in attitude through suction of air from the flow field into a slot near the trailing edge of the airfoil upper surface. By removing the air through the slot a sink effect is formed at the slot and thus, theoretically, to satisfy the Kutta condition at the trailing edge of the airfoil, an increase in circulation is necessary.

To avoid confusion, it must be noted that there is a sharp distinction drawn herein between boundary-layer control and circulation control by suction. Boundary-layer control is a method of overcoming the reductions in lift caused by air-flow separation due to viscous effects. Therefore, in the broadest sense, boundary-layer control can also be considered a form of circulation control since when air-flow separation is prevented with boundary-layer control an increase in circulation is obtained. Circulation control by suction, however, is a method of increasing circulation in the absence of any viscous effects; for example, at an attitude of 0° where the viscous effects on the lift are essentially zero for a symmetrical airfoil section, an increase in lift is obtained with circulation control.

Ehlers' theory indicates that the variables which control the effectiveness of circulation control are: first, the quantity of air removed from the flow field; second, the chordwise extent and position of the slot relative to the trailing edge; third, the thickness of the airfoil section; and fourth, the thickness distribution. The increment of lift obtainable with circulation control can be expressed roughly as

$$\Delta c_l = K\sqrt{c_Q}$$

This expression is for a slot at the airfoil trailing edge which, according to theory, is the most effective type of slot. The foregoing expression is exact for slots of zero width located at the trailing edge. In this case, the constant K is primarily a function of airfoil thickness; for example, for a flat plate the constant is equal to 10.0, whereas for an airfoil section having 15-percent-chord thickness the constant is equal to 10.7 and for a circle the constant is equal to 14.1. Thus, in the usual range of airfoil thicknesses, thickness variation has little effect on circulation control when compared with the effect of flow coefficient. For slots having finite width and extent from the trailing edge, which would be the practical case, the foregoing expression for lift increment is not exact. However, the expression can still be used to indicate the effect of chordwise extent of slot on lift increment at a given flow coefficient. For example, for a 15-percent-thick section at a flow coefficient of 0.03, the value of K varies from a maximum value of 10.7 for a slot of zero width at the trailing edge to a value of 8.1 for a 1-percent-chord slot and to a value of 7.0 for a 3.0-percent-chord slot. From the foregoing, based on Ehlers' theory, it can be concluded that the primary control of lift increment is the direct effect of flow coefficient, that slot geometry has an important effect, and that airfoil thickness and thickness distribution have relatively small effects.

In view of the limited research on circulation control, the main emphasis of this report will be directed toward determining the effectiveness of circulation control on a relatively thin section and also determining whether the trends indicated by theory are applicable to a three-dimensional sweptback wing. The first phase of the report will show the correlation of the two-dimensional-section results with theory. The second phase will indicate the magnitude of lift obtainable and the power requirements for circulation control on a three-dimensional sweptback wing. The third phase will indicate the effect of slot width and slot depth on circulation control. The fourth phase will show the effect of split-flap deflection on circulation control, and the fifth phase will show the effectiveness of circulation control over a range of angles of attack and will indicate the effect of circulation control on air-flow separation.

Correlation of Two-Dimensional-Section Results With Ehlers' Theory

The results of tests made with circulation control applied to the two-dimensional airfoil section are shown in figure 6 and are compared to theoretical variations of lift with flow coefficient based on Ehlers' theory (ref. 1) and to the theory of reference 3. The values of lift increment, Δc_l, for the experimental results are the values of

lift increment due to circulation control obtained by suction only. For all slots that were tested having chordwise extents less than 3.1-percent chord, it was necessary to deflect the lower surface to provide sufficient depth of slot for air to pass through the slot. The results for the slot having 3.1-percent chordwise extent and a depth of 0.5-percent chord formed with no lower surface deflection indicate that the experimental values of lift coefficient are approximately 20-percent lower for a given flow coefficient than Ehlers' theoretical values for a 3.0-percent slot for a flat plate. The results obtained with the 1-percent-chord slot having 1-percent-chord depth formed by deflecting the lower surface approximately 1.8° indicate that greater lifts can be obtained with suction than are indicated by theory for the 1.0-percent slot on a flat plate. Up to a flow coefficient of 0.02 the results are essentially equal to the maximum theoretical variation, $\Delta c_l = 10\sqrt{c_Q}$, which is predicted for the case of a slot of 0-percent chord located at the trailing edge of a flat plate. For both 3.1- and 1.0-percent-chord slot configurations the experimental data are in much better agreement with Ehlers' theory than with the theory of reference 3. The results for the third slot, having a chordwise extent of 1.0-percent chord and a depth of 1.3-percent chord, indicated that larger values of lift can be obtained than the maximum predicted by theory at flow coefficients above about 0.01.

Therefore, based on the two-dimensional results, it can be concluded that, first, the maximum variation of lift increment with flow coefficient estimated by Ehlers' theory gives a reasonable indication of value of lift which can be obtained with circulation control applied to a relatively thin airfoil section (slot extent and depth about 1-percent of chord); second, the theory does give the proper trends for the effects of chordwise extent of the slot relative to the trailing edge; and third, the results indicate that a slight deflection of the lower surface may have considerable effect on the lift obtainable with circulation control, an effect which is not considered in Ehlers' theory.

Effectiveness of Circulation Control on a Sweptback Wing

The results of tests obtained with circulation control applied to a 45° sweptback wing for the trailing-edge slot that gave the largest increase in lift with flow coefficient will be discussed herein. These results were obtained with a trailing-edge slot having 1-percent-chord extent and 1.3-percent-chord depth and are shown in figures 7, 8, and 9 for an angle of attack of 0°. The variation of wing lift coefficient with total flow coefficient, the corresponding changes in pitching moment, and the suction pressure coefficients required are shown in

figure 7. The section pressure distributions at five spanwise sections corresponding to the various flow coefficients are shown in figure 8 and the spanwise variation of section lift coefficient for the respective flow coefficients is shown in figure 9.

The data indicate that considerable increase in lift can be obtained with circulation control with no increase in incidence, in this case an increment of lift coefficient of about 0.45. However, it is believed that larger lift increments could be obtained with more optimum installations. It is fairly certain that the maximum lift increment was limited, at least partially, due to the fact that the section values of suction flow coefficient at the inboard sections and the outboard sections of the wing fell off considerably below the values in the region of the mid-semispan.

In assessing the practicality of achieving high lifts through circulation control it is of interest to estimate from the two-dimensional results the maximum values that could be realized and the corresponding cost in power. It is first necessary to demonstrate that the two-dimensional results can be applied to the three-dimensional case with an acceptable degree of accuracy. Such a demonstration is given in the Appendix; while a considerable degree of approximation is involved, it is believed sufficiently accurate for the stated purpose of a preliminary look at the practicality of circulation control on an airplane.

The power reduction possible through adequate control of spanwise suction air flow is indicated by the following comparison. The power required to obtain a lift coefficient increment of 0.38 for the case investigated (slot $s/c' = 0.01$, $d/c' = 0.013$) is compared with that required provided all the sections were operating at equal section lift coefficients of 0.43 over a major portion of the span to give a total lift coefficient of 0.38; a section flow coefficient of 0.0095 would be required in this latter condition. In this instance the total flow coefficient would be reduced from a value of 0.0064 to 0.0060 while the power would be reduced from a value of 73 horsepower to an ideal value of 42 horsepower for a free-stream velocity of 100 miles per hour. (Equivalent duct losses have been assumed in each case.) Some of the reduction in horsepower is due to the lower suction pressures that would be required with a uniform distribution of section lift increment, whereas with nonuniform spanwise distribution higher suction pressures would be required in the regions where the section lift increments were considerably greater than the lift increments for the case with uniform distribution. For a full-scale airplane of 400 square feet of wing area and a wing loading of 40 pounds per square foot, the power required in level flight to obtain the total lift coefficient of 0.38 would be 850 horsepower for this ideal installation.

In the two cases just compared, the simple sweep analysis indicates that the section lifts did not or would not reach the value of lift coefficient where the two-dimensional lift coefficient ceased to rise rapidly with flow coefficient (figure 6 up to flow coefficients of about 0.015). If now it is assumed that full flow control were obtained for the model having the same trailing-edge slot ($s/c' = 0.01$, $d/c' = 0.013$) with a section flow coefficient of 0.015 existing across the entire span, then from considerations of simple sweep theory and the two-dimensional results of figure 6 a wing lift increment of approximately 0.65 would be predicted, assuming that the two-dimensional results were directly applicable. In any case, this would be the most optimistic value of lift increment obtainable. However, the power required would be very large for a full-scale airplane of 400-square-foot wing area and a wing loading of 40 pounds per square foot. The flow coefficient required based on the total wing area and the free-stream velocity of 155 miles per hour would be approximately 0.01. If it is assumed that the duct losses and suction pressure coefficient are equivalent to those for the model of this investigation then the power required would be approximately 2,400 horsepower. It is therefore concluded that based on this investigation, the use of circulation control with no change in attitude as a high lift device will require a large source of power. Although some gains possibly could be made with improved slot design, these reductions would be small compared to the over-all power requirements necessary due to the large flow quantities. It should be noted that the power requirements would be less at higher angles of attack than 0° due directly to the lower forward speeds and this will be discussed in a later section of the report.

Effect of Slot Configuration on Circulation Control

A variable that, according to Ehlers' theory, has a significant effect on determining the lift increment obtainable with circulation control is the chordwise extent of the slot from the trailing edge. This variable has an effect only if the slots are reasonably close to the trailing edge and then the effectiveness of circulation control theoretically will increase as the slot position approaches the trailing edge, with the maximum values of lift obtained with suction at the trailing edge. For the case with slots significantly distant from the trailing edge, theoretically the lift increment obtainable will be dependent only upon the quantity of flow removed regardless of slot position.

A variable that was not considered in Ehlers' theory is the effect of small deflections of the lower surface near the trailing edge, as shown in figure 3. In these tests, as discussed previously, these deflections were necessary to form slots of sufficient depth to allow the air to be drawn into the wing.

The two-dimensional results discussed previously indicated that both of these variables, slot extent and lower-surface deflection, had an appreciable effect on the lift obtainable with circulation control. To determine whether the same trends are true with circulation control applied on a 45° sweptback wing, and to determine whether the slot for which the data were obtained was near the optimum, data were obtained with various slot configurations. It must be noted that the spanwise distribution of suction may have changed with changes in the area of the suction slot. Therefore, the results indicated in the following sections may not be applicable to wings having duct configurations which differ from the test model.

Chordwise extent of slot.- The variation of the lift increment, due to circulation control, with flow coefficient is given in figure 10 for various chordwise extents of slot, all having the same lower-surface deflection and hence having approximately the same slot depth. The results are shown in figure 11 as a function of chordwise slot extent and indicate that for slot extents greater or less than 0.9-percent chord the effectiveness of circulation control is reduced. From the results, it appears that Ehlers' theory indicates proper trends for slot extents larger than 0.9-percent chord. The loss in effectiveness for slots having smaller chordwise extent than 0.9 percent is believed to be due to air being drawn into the slot from the lower surface as well as the upper surface which would tend to cause a loss in circulation; this effect will be discussed further in the section concerned with circulation control applied in conjunction with a trailing-edge split flap.

Depth of slot.- The variation of lift increment, due to circulation control, with flow coefficient for various depths of slot having a chordwise extent of 0.6-percent chord is shown in figure 12. The results are shown in figure 13 as a function of slot depth and indicate that for the 0.6-percent-chord slot an increase in the effectiveness of circulation control is obtained with increases in slot depth up to about 1.1-percent chord. With slots depths greater than 1.1 percent, a decrease in effectiveness is obtained. However, from the results of tests of a number of slots depths, figure 14, it appears that each slot depth investigated has an optimum chordwise extent. It can be concluded that for the various chordwise extents of slots tested the depth of slot or the deflection angle of the lower surface was found to be an important variable as the results indicate that this variable can alter the resultant lift gain with circulation control by as much as 100 percent.

Effect of Trailing-Edge Split Flap on Circulation Control

In an effort to increase the lift obtained by circulation control, a trailing-edge split flap was deflected 45° and 55°. The results are shown in figures 15 and 16 for an angle of attack of approximately 0°. The results are given for a full-span slot (slot chordwise extent of 0.4-percent chord and slot depth of 1.2-percent chord) that gave the largest increase in lift with the flaps deflected. The lift increments due to circulation control with flap deflections 45° and 55° are approximately equal and for any value of flow coefficient available are greater than obtained with no flap deflection. In each case, a maximum increment of lift of about 0.61 was obtained with a flow coefficient of 0.014 with the split flaps deflected, whereas with no flap deflection and with a flow coefficient of 0.0158 the largest increment of lift obtained was 0.45.

As in the case of no flap deflection, the effect of chordwise slot extent on circulation control applied with a split-flap deflection of 45° was studied. The results are shown in figure 17 as the variation of lift increment due only to circulation control with slot chordwise extent for the slot depth (approximately 1.2-percent chord) that gave the largest increase in lift. The lower-surface deflection for this study was the same as for the previous study of slot extent with zero flap deflection. A comparison of figure 17 with figure 11 (which is for no flap deflection) shows that an increase in the effectiveness of circulation control was realized when the flaps were deflected. For flow coefficients above 0.004, the magnitudes of lift and the trends are essentially the same for both cases for slot extents greater than 0.9-percent-chord slot. However, with the split flap deflected the effectiveness of circulation control continues to increase as the slot extent is decreased to 0.4-percent chord, whereas with no flap deflection the effectiveness of circulation control decreases with slot extents less than 0.9-percent chord. The trend of increased effectiveness of circulation control with decreased chordwise extents of slot with the split flaps deflected is believed to be due to the effect the flaps have on the flow at the trailing edge. With the flaps deflected the streamlines in the region of the trailing edge are turned downward. Hence, with smaller chordwise extents of slot than 0.9-percent chord, the air continues to be taken into the slot from the upper surface rather than from the lower surface as was believed to be the case with no flap deflection and the small slot extents. Therefore, an increase in circulation is obtained with the air removed from the flow field of the upper surface through slots nearer the trailing edge, as was indicated by theory.

The effect of slot depth or lower-surface deflection on circulation control with the split flaps deflected is generally the same as discussed

previously without a flap deflection. The results are shown in figure 18 for chordwise slot extent of 0.6 percent and indicate the slot-depth variable has a large effect on the increment of lift attainable with circulation control.

Effect of Circulation Control on Pitching Moment

The pitching-moment changes associated with the increase in lift due to circulation control are shown for an angle of attack of approximately 0° in figure 7 for 0° of flap deflection and in figure 15 for 45° and 55° of flap deflection. In each case the pitching-moment changes associated with circulation control are large. For example, a comparison between the pitching-moment variation with circulation control and that associated with a split-flap deflection indicates that for an equal increment of lift the pitching-moment change with circulation control is nearly twice as large as that given by the partial-span split flap ($\Delta C_m/\Delta C_L \simeq 0.5$ with circulation control and $\Delta C_m/\Delta C_L \simeq 0.3$ for deflection of split flap). Similar large changes in pitching moment accompanied the increases in lift with circulation control when applied with the split flaps deflected. The reason for the large negative increase in pitching moment is indicated by the change in the chordwise distribution of pressures on the upper surface with circulation control applied, shown in figure 8 with 0° flap deflection and in figure 16 with the flaps deflected 45°.

Circulation Control at Angle of Attack

The results of applying circulation control to an aircraft wing have thus far been presented only at an angle of attack of approximately 0°. Theory indicates that the increment of lift obtainable with circulation control should remain essentially constant with angle of attack provided that no air-flow separation is occurring on the wing or airfoil section. Investigations were undertaken on the 45° sweptback wing to determine the effectiveness of circulation control on the sweptback wing over a range of angles of attack and the effect that air-flow separation on the wing would have on the effectiveness of circulation control.

The static longitudinal results with circulation control applied to the 45° sweptback wing are shown in figures 19 and 20 for 0°, 45°, and 55° of flap deflection. The results are shown for suction applied to only the slots that, for each flap deflection, gave the largest increases in lift coefficient at an angle of attack of 0°. In figure 19, the lift, drag, and pitching-moment characteristics are shown for

circulation control applied to the slot having 1.0-percent chordwise extent and 1.3-percent-chord depth with the flaps at zero deflection. The increment of lift due to circulation control is essentially constant up to an angle of attack of 4.2°. At higher attitudes leading-edge air-flow separation, which began at the outboard sections and progressed toward the root with increases in angle of attack, resulted in large reductions in the increment of lift obtained with circulation control. The loss in effectiveness occurred first at spanwise sections where air-flow separation was occurring. Similar trends with angle of attack are shown by the force data in figure 20 where circulation control was applied to the wing with 45° and 55° of split-flap deflection.

To study the effectiveness of circulation control at higher angles of attack than those shown in figure 20, area suction was applied through a porous surface at the wing leading edge to delay air-flow separation. The results of these tests with the split flaps deflected 45° are shown in figure 21 and indicate that the effectiveness of circulation control remained essentially constant up to an angle of attack of about 14° where air-flow separation occurred on the wing. The flow-coefficient and pressure-coefficient requirements for the circulation control and the requirements for leading-edge area suction are given in table IV for the data presented in figures 20 and 21. Based on the results shown in figure 21 and table IV, the power requirements were calculated for an airplane of 400 square feet and a wing loading of 40 pounds per square foot. The results are shown in figure 22 for a range of angles of attack. Although the power requirements are reduced considerably with increasing angle of attack, the requirements are still very large with the distribution of suction obtained in this investigation.

CONCLUDING REMARKS

The results of a wind-tunnel investigation of circulation control applied by suction of air through slots at the trailing edge of a swept-back wing indicate the following: (1) Considerable increase in lift can be realized on sweptback wings with this type of circulation control, (2) the trends indicated by theory and two-dimensional section results are applicable to a sweptback wing, (3) this type of circulation control remains effective throughout the angle-of-attack range when no air-flow separation is occurring on the wing, and (4) large power requirements are necessary to obtain a sizable increase in lift with circulation control.

For the particular model under investigation, an increment of lift of 0.45 was obtained with a flow coefficient of 0.014 with no flap deflection, and an increment of lift of 0.6 was obtained with a flow coefficient of 0.014 with split flaps deflected 45°. The increment of

lift obtained with circulation control is accompanied by large increases in the negative value of pitching moments.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Sept. 21, 1954

APPENDIX

CORRELATION OF TWO-DIMENSIONAL SECTION DATA

WITH SWEPTBACK-WING DATA

As pointed out previously in the text, the spanwise distribution of flow coefficient was not uniform for the sweptback-wing tests and hence the results are probably not an indication of the maximum value of lift obtainable with circulation control for the available suction power. To obtain an indication of the magnitude of suction power requirements and also possible lift increments obtainable with a uniform spanwise distribution of suction, the two-dimensional section results were used to estimate the values of lift and power for the sweptback wing for purposes of considering possible application of circulation control to airplanes.

A correlation between the three-dimensional swept-wing results and the two-dimensional section results is made herein to substantiate the use of the two-dimensional section results with circulation control for making the foregoing estimations. The correlation is made for the same slot configuration for the three-dimensional and two-dimensional models, having a 1.0-percent-chord extent and 1.3-percent-chord depth in each case. Inasmuch as the actual values of suction flow coefficient were not measured at various spanwise sections of the sweptback wing, it was necessary to use an indirect method of correlation. It was assumed that the differences in airfoil shape and thickness of the two-dimensional section and the airfoil section normal to the quarter-chord line would have little or no effect at least within the accuracy of this approximate correlation.

Procedure

The specific steps in making the correlation were as follows. First, the simple sweep concept was applied to the negative pressure at 97.5-percent chord obtained from figure 8 for the various spanwise sections and flow coefficients by the following relation

$$P_n = \frac{P}{\cos^2 \Lambda}$$

where P is the pressure coefficient based on the free-stream velocity, P_n is the pressure coefficient based on the normal component of the free-stream velocity, and Λ is the sweepback angle of the quarter-chord line.

Second, with the normal value of pressure coefficient known, the section lift coefficient due to circulation control based on the normal component of velocity was determined from the two-dimensional section data shown in figure 23 where the variation of section lift with surface pressure coefficient at the 97.5-percent chordwise section is shown. Third, the section flow coefficients were then determined, for the 1.0-percent-chord slot with 1.3-percent-chord depth, from the curve shown in figure 6. Finally, the flow quantities and section lifts were summed up across the span. The following relation was used to obtain the total flow coefficient, assuming that both wing panels were identical in lift and flow distribution.

$$C_Q = \frac{2}{U_o S} \int_o^{l/2} c_Q c_n U_{o_n} dy$$

where l is the spanwise length of the trailing edge. A comparison between the measured and calculated lift coefficients and flow coefficients is given in the following table:

Measured ΔC_L	Measured C_Q	Calculated ΔC_L	Calculated C_Q	Percent error in C_Q
0.18	0.0026	0.18	0.0018	30.7
.38	.0064	.36	.0054	15.6
.43	.0099	.45	.0082	18.2
.44	.0136	.51	.0103	24.2
.45	.0158	.56	.0129	18.3

The comparison of the lift increments calculated and measured for the particular values of measured flow coefficients is shown in figure 24. It should be noted that the entire procedure is subject to several limitations which if they could have been accounted for would have made a difference in the correlation.

1. The section data were obtained with a deflected nose flap, whereas the three-dimensional data were obtained with no nose-flap deflection and appear to be affected by air-flow separation at the higher values of flow coefficient as indicated by the pressure distributions of figures 8(e) and 8(f).

2. The spanwise distributions of section lift coefficient calculated by this method are considerably different from the measured distribution shown in figure 9.

3. The loading induced at the tip sections when circulation control is applied inboard and the carry-over of loading across the fuselage were not accounted for.

Despite the relative grossness of this correlation, it is believed to be of sufficient value to justify the analysis and conclusions made in the text. It does not appear that the inadequacies of the analysis would lead to appreciable error in the calculated power required for the idealized cases based on available two-dimensional results and uniform suction distribution.

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2. Regenscheit, B.: Tests on a Wing With Suction at the Trailing Edge. Ministry of Supply (British), Völkenrode (Rep. and Trans. 477), Ministry of Supply GDC 10/1341T. From: (ZWB, Berlin) FB 1594, Jan. 1947.

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6. Cook, Woodrow L., and Kelly, Mark W.: The Use of Area Suction for the Purpose of Delaying Separation of Air Flow at the Leading Edge of a 63° Swept-Back Wing - Effects of Controlling the Chordwise Distribution of Suction-Air Velocities. NACA RM A51J24, 1951.

TABLE I.- COORDINATES IN PLANES PERPENDICULAR TO WING LEADING EDGE OF THE 45° SWEPTBACK WING, PERCENT CHORD

Station	Ordinate
0	0
.362	.773
.543	.933
.906	1.181
1.819	1.629
3.664	2.258
5.534	2.737
7.432	3.141
12.311	3.791
15.302	4.309
19.410	4.714
23.645	5.030
28.011	5.247
32.511	5.369
37.158	5.356
41.950	5.221
46.899	4.892
52.011	4.654
57.301	4.249
62.711	3.768
68.432	3.220
74.295	2.629
80.373	2.014
86.669	1.377
93.208	.715
100	.028
Leading-edge radius = 0.863.	

TABLE II.- LOCATION OF PRESSURE ORIFICES

Spanwise positions of orifices		Chordwise positions[1] of orifices (on upper and lower surfaces at each station)	
Station number	Percent semispan	Orifice number	Percent chord
1	24.0	1	0
2	41.2	2	.25
3	58.5	3	.5
4	75.7	4	1.0
5	93.0	5	1.5
		6	2.5
		7	5.0
		8	7.5
		9	10.0
		10	15.0
		11	20.0
		12	30.0
		13	40.0
		15	60.0
		16	70.0
		17	80.0
		18	90.0
		19	95.0
		20	97.5

[1]Orifices omitted:

Station 1: upper-surface numbers 3 and 5, lower-surface numbers 3, 4, 5, and 13.

Station 2: upper-surface number 11, lower-surface numbers 10, 11, and 17.

Station 3: upper-surface numbers 5 and 6, lower-surface numbers 3, 10, and 11.

Station 4: lower-surface numbers 3, 9, 10, and 11.

Station 5: upper-surface numbers 15, 18, and 19, lower-surface numbers 3, 5, and 10.

TABLE III.- TRAILING-EDGE SUCTION SLOT DIMENSIONS

Slot dimension	Slot designation	A	B	C	D	E	F	G
s/c'	1	---	---	---	---	0.013	0.020	---
d/c'		---	---	---	---	.004	.005	---
s/c'	2	---	---	0.005	---	.013	.020	0.028
d/c'		---	---	.005	---	.005	.006	.008
s/c'	3	---	0.004	.006	0.010	.012	.020	.029
d/c'		---	.010	.010	.010	.011	.012	.013
s/c'	4	0.003	.004	.006	.010	.013	.020	---
d/c'		.012	.012	.013	.013	.014	.015	---
s/c'	5	---	.005	.007	---	.016	.022	---
d/c'		---	.021	.021	---	.023	.024	---

TABLE IV.- FLOW AND PLENUM-CHAMBER PRESSURE COEFFICIENTS

(a) Table for figure 20

	$\delta_f = 45^\circ$		$\delta_f = 55^\circ$	
α	C_L	$C_{Q_{TE}}$	C_L	$C_{Q_{TE}}$
0.4	1.05	0.0162	1.07	0.0140
4.3	1.26	.0166	1.25	.0143
8.3	1.24	.0147	1.23	.0148
10.4	1.22	.0152	1.20	.0157
12.4	1.17	.0154	1.17	.0157

(b) Table for figure 21

α	C_L	$C_{Q_{TE}}$	$C_{Q_{LE}}$	$C_{P_{TE}}$	$C_{P_{LE}}$
0.2	1.05	0.0130	---	-34.0	---
4.3	1.28	.0131	0.0017	-34.2	-5.0
8.4	1.50	.0134	.0019	-35.0	-8.3
10.5	1.59	.0135	.0024	-35.0	-11.7
12.6	1.66	.0137	.0026	-36.0	-13.2
14.6	1.71	.0140	.0027	-37.7	-15.0
15.6	1.62	.0121	.0032	-30.2	-15.2
16.4	1.54	.0123	.0031	-30.5	-15.0

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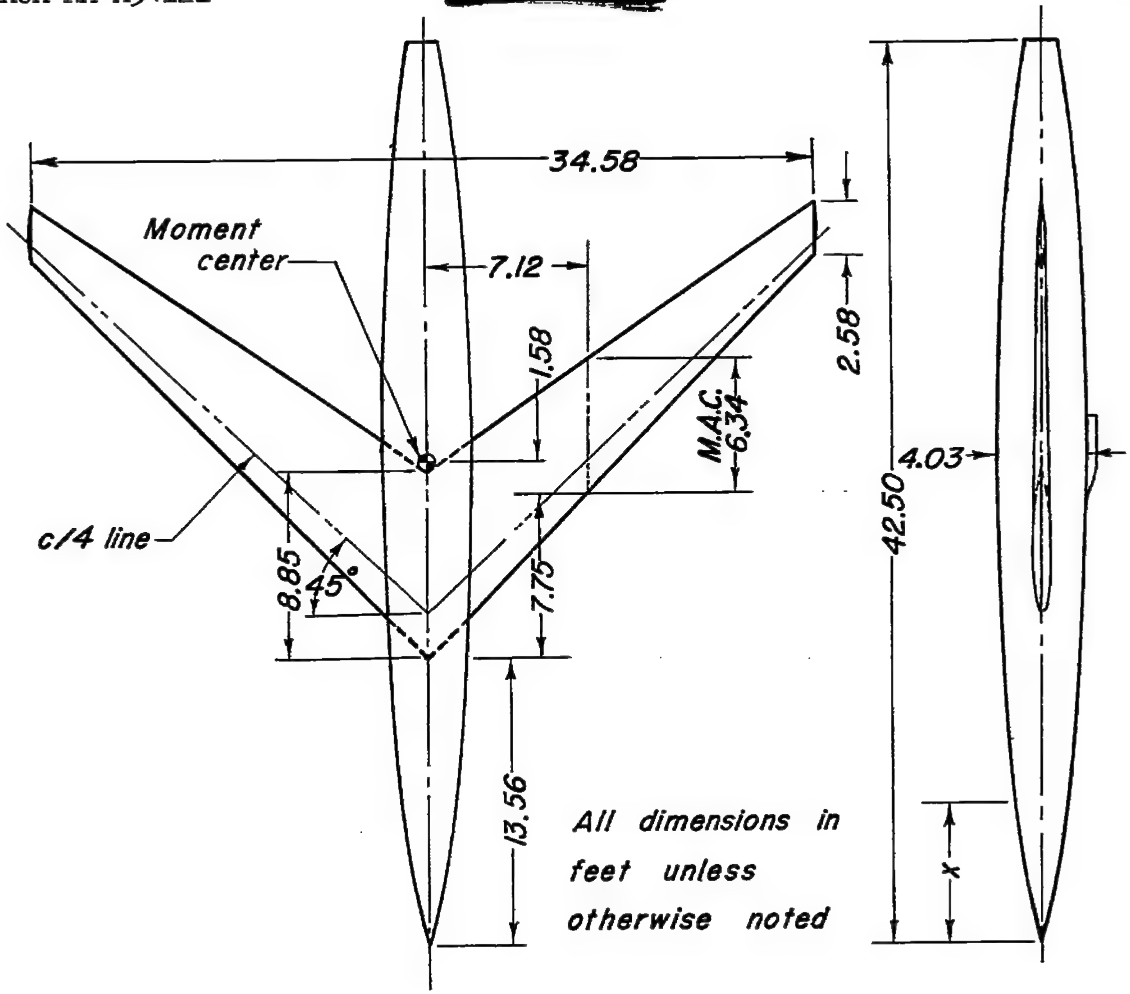

Wing	
Sweep	45°
Aspect ratio	6.0
Taper ratio	0.292
Twist	0°
Dihedral	0°
Incidence	0°
Area	198.8 sq ft
Fuselage	
Fineness ratio	10.5
Radius at station x	$2.016[1-(\frac{x}{23}-1)^2]^{3/4}$ ft

Figure 1.- Geometric characteristics of the model tested.

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[redacted]

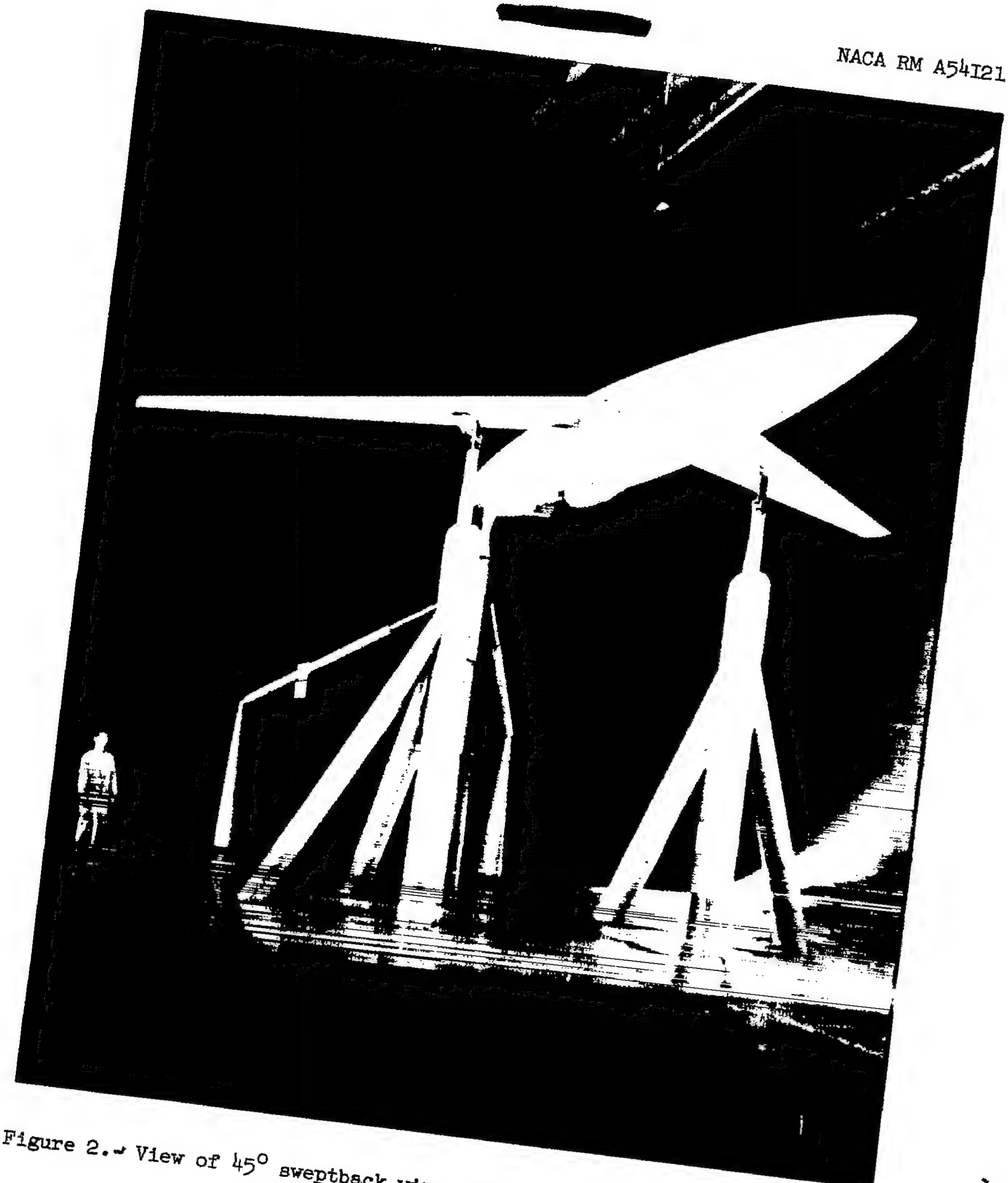

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Figure 2.- View of 45° sweptback wing model mounted in the 40- by 80-foot wind tunnel.

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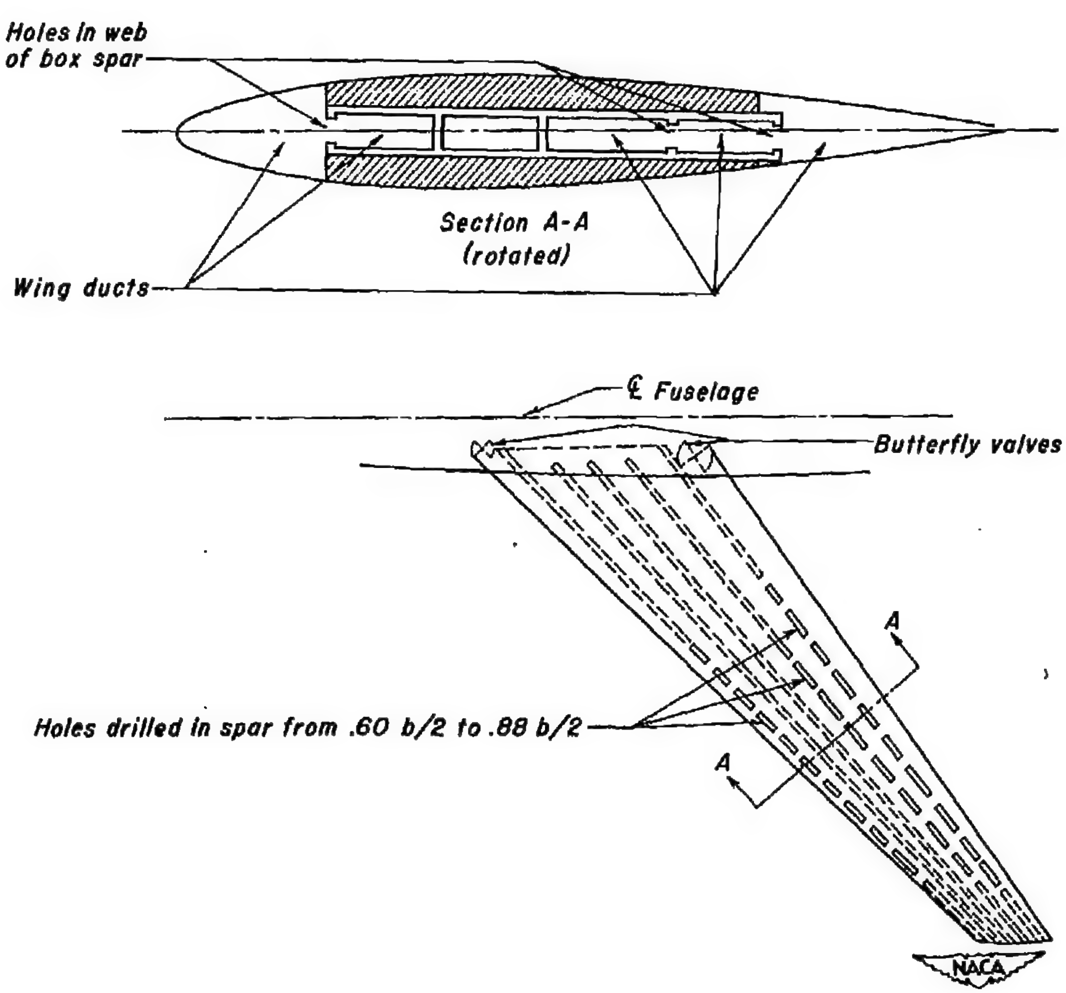
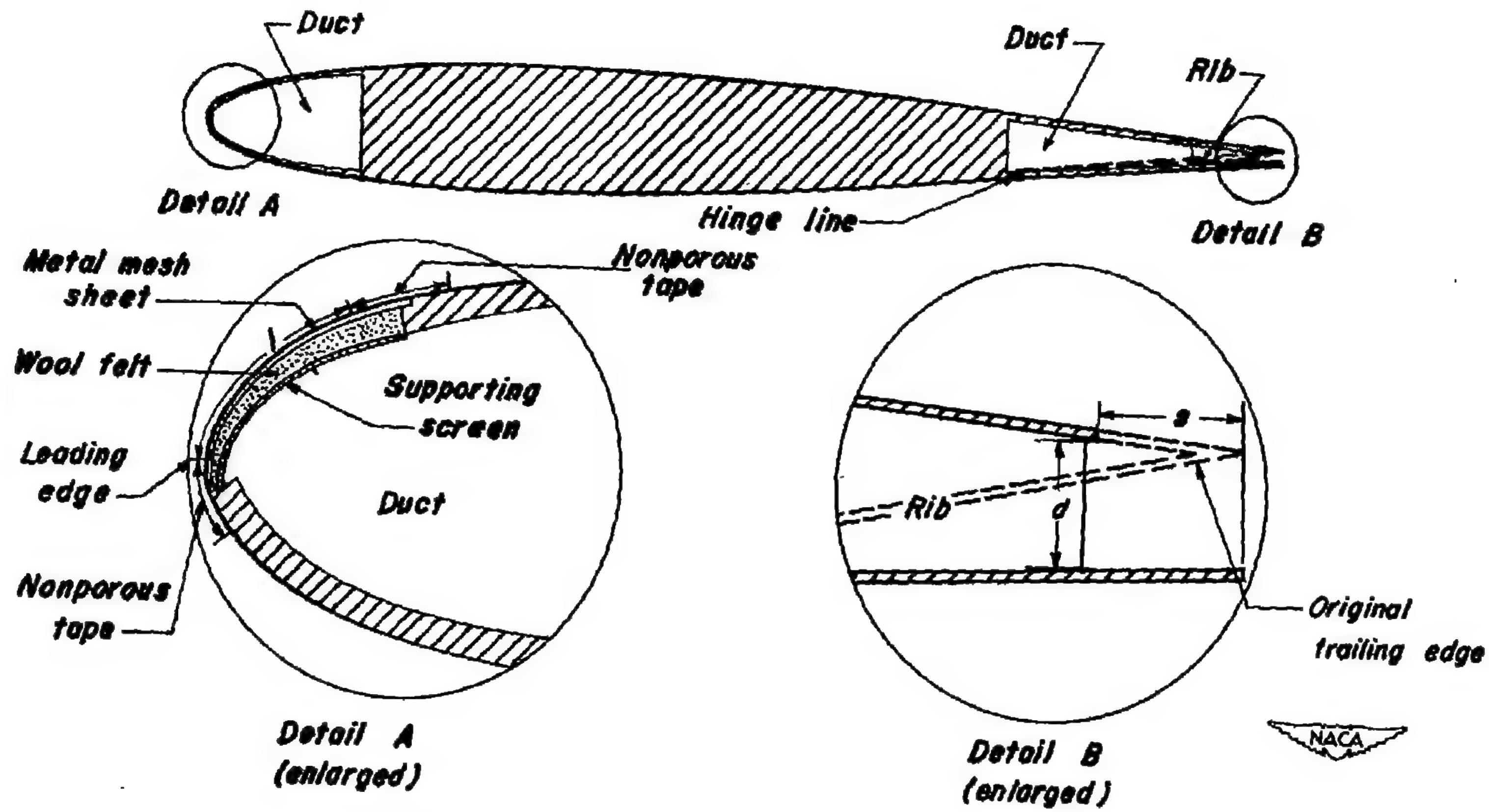


(a) Ducting in wing.

Figure 3.- Schematic diagram of wing.



(b) Porous leading-edge and trailing-edge slot.

Figure 3.- Concluded.

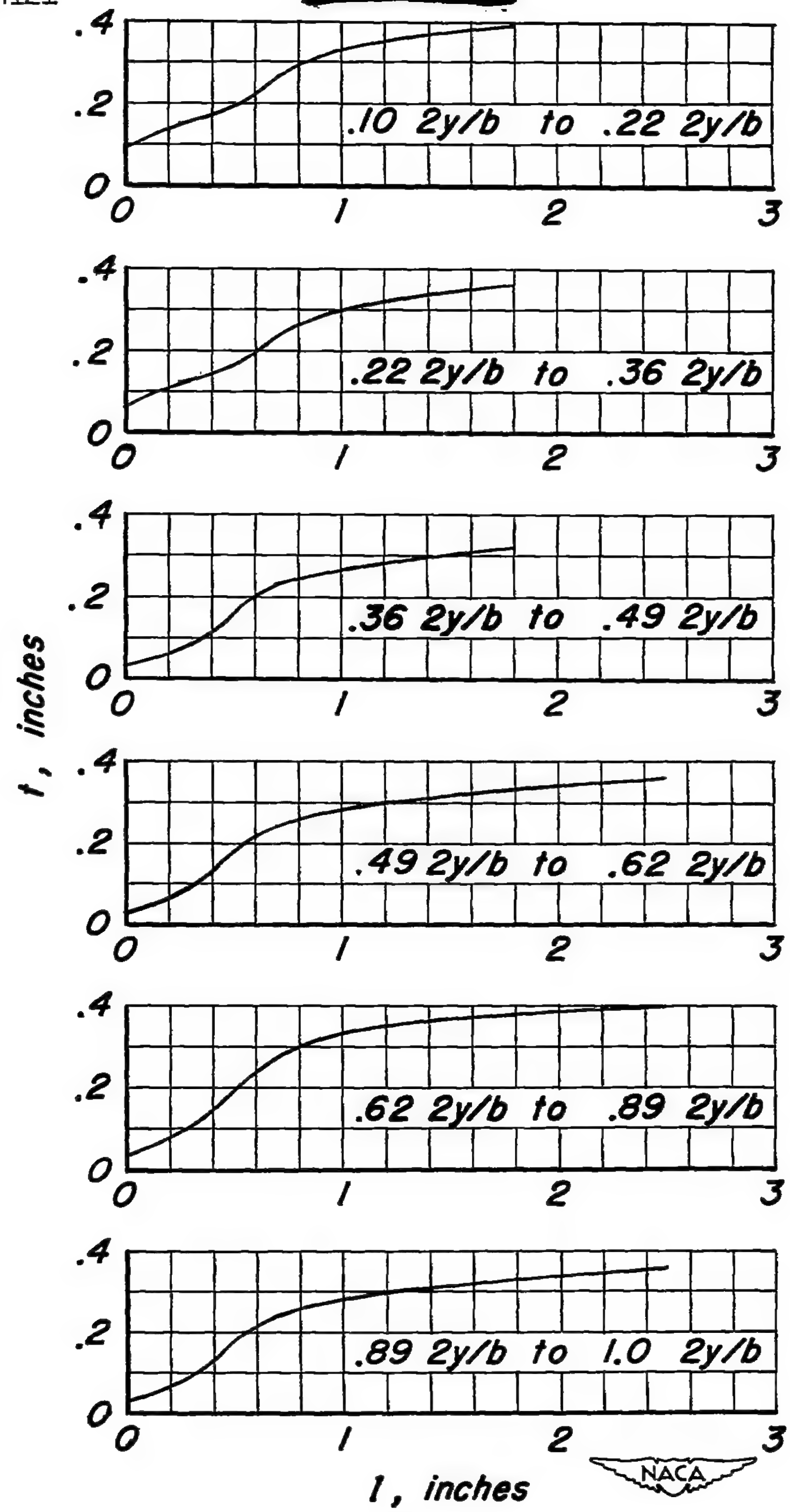


Figure 4.- Thickness variation of the felt backing used in the wing leading edge.

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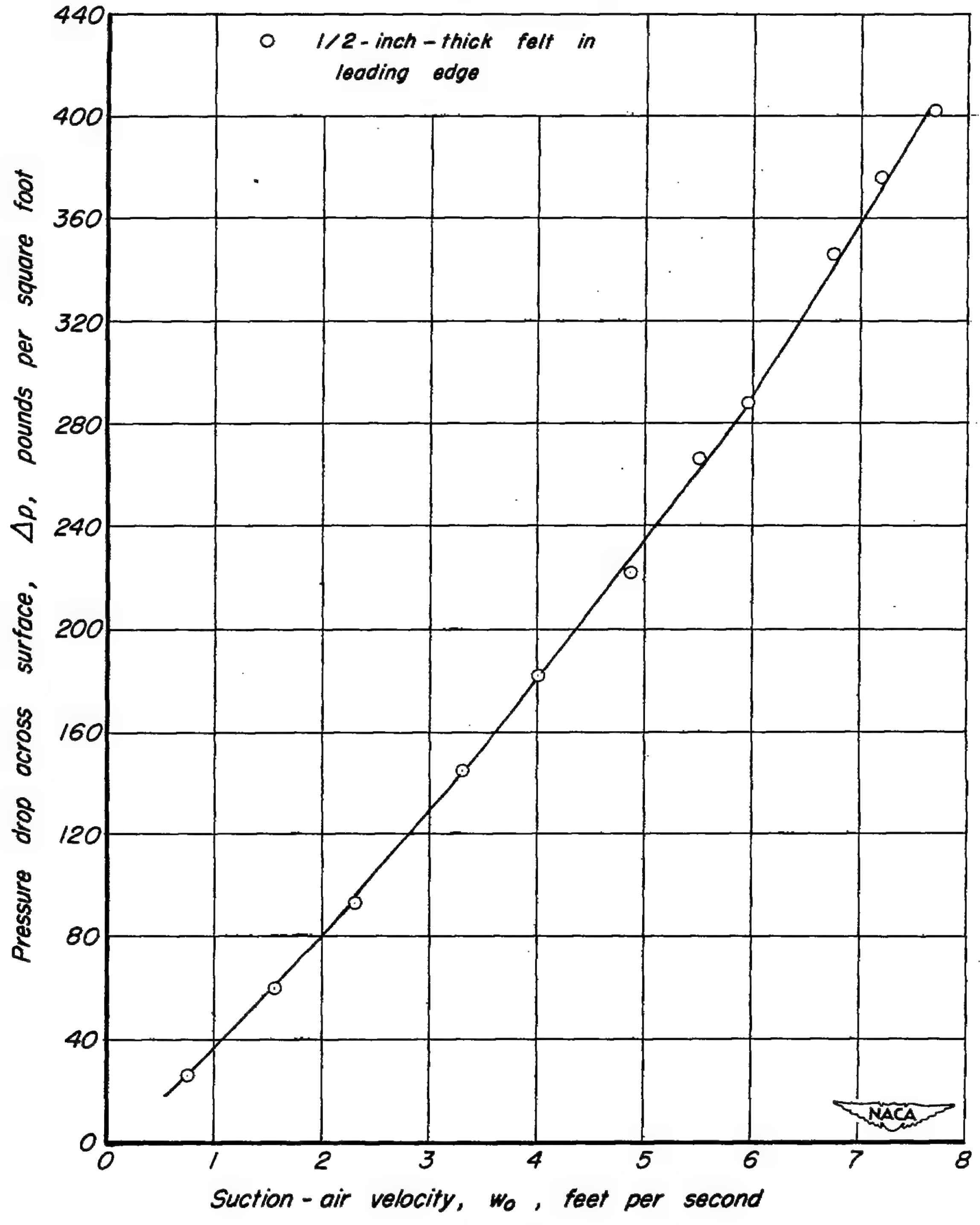


Figure 5.- Calibration of suction-air velocities for porous mesh sheet backed with one-half-inch wool felt material.

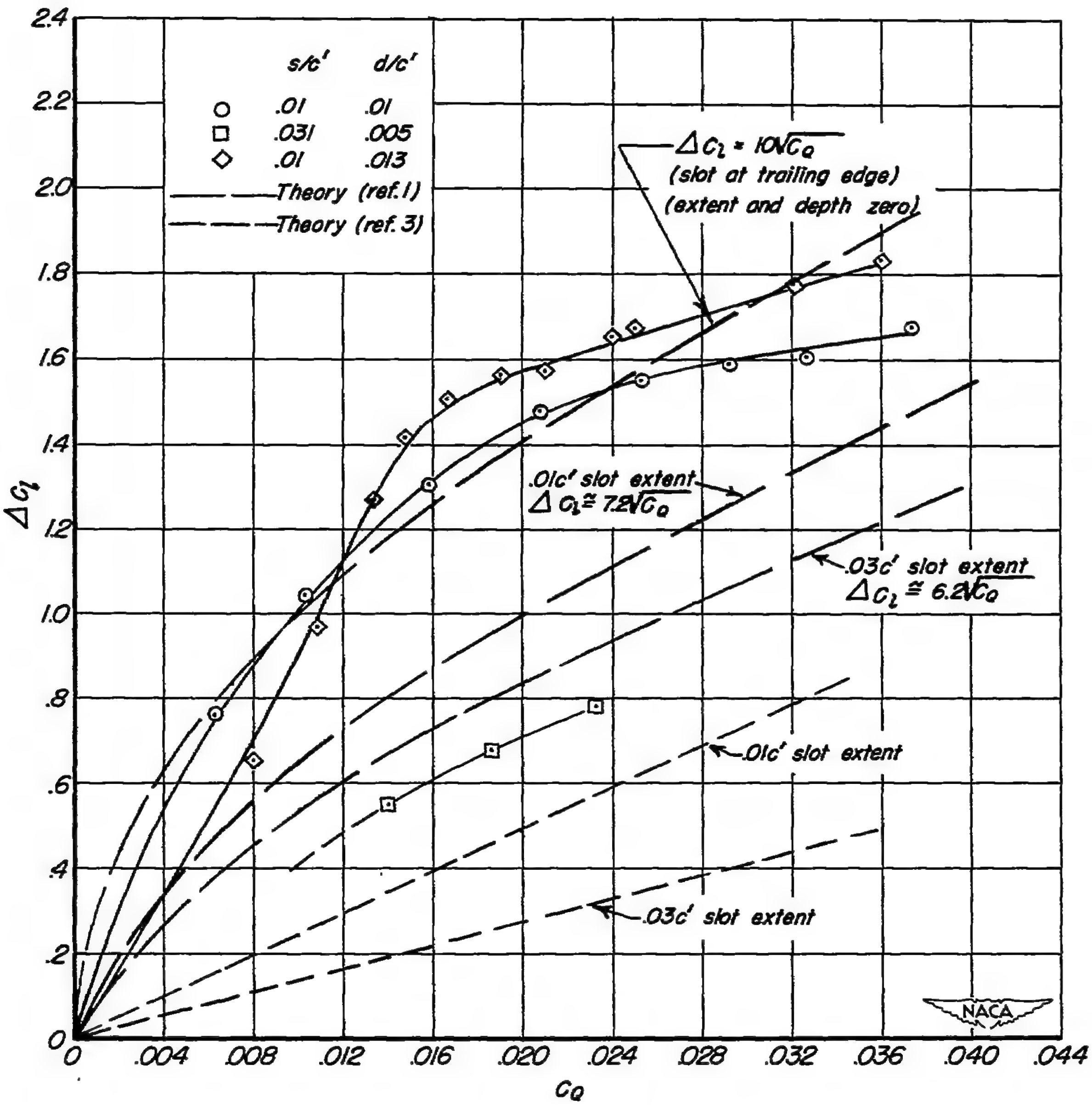


Figure 6.- Comparison of two-dimensional section data and theory for a flat plate.

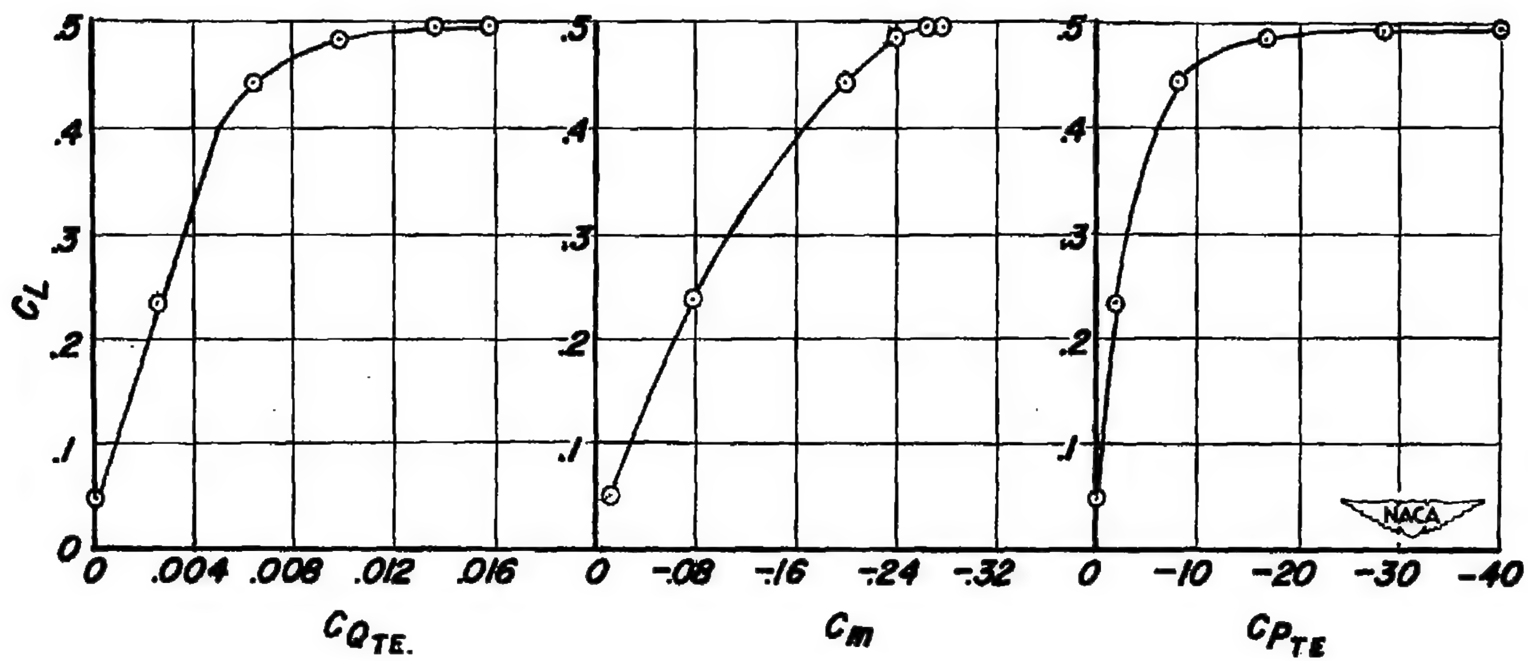
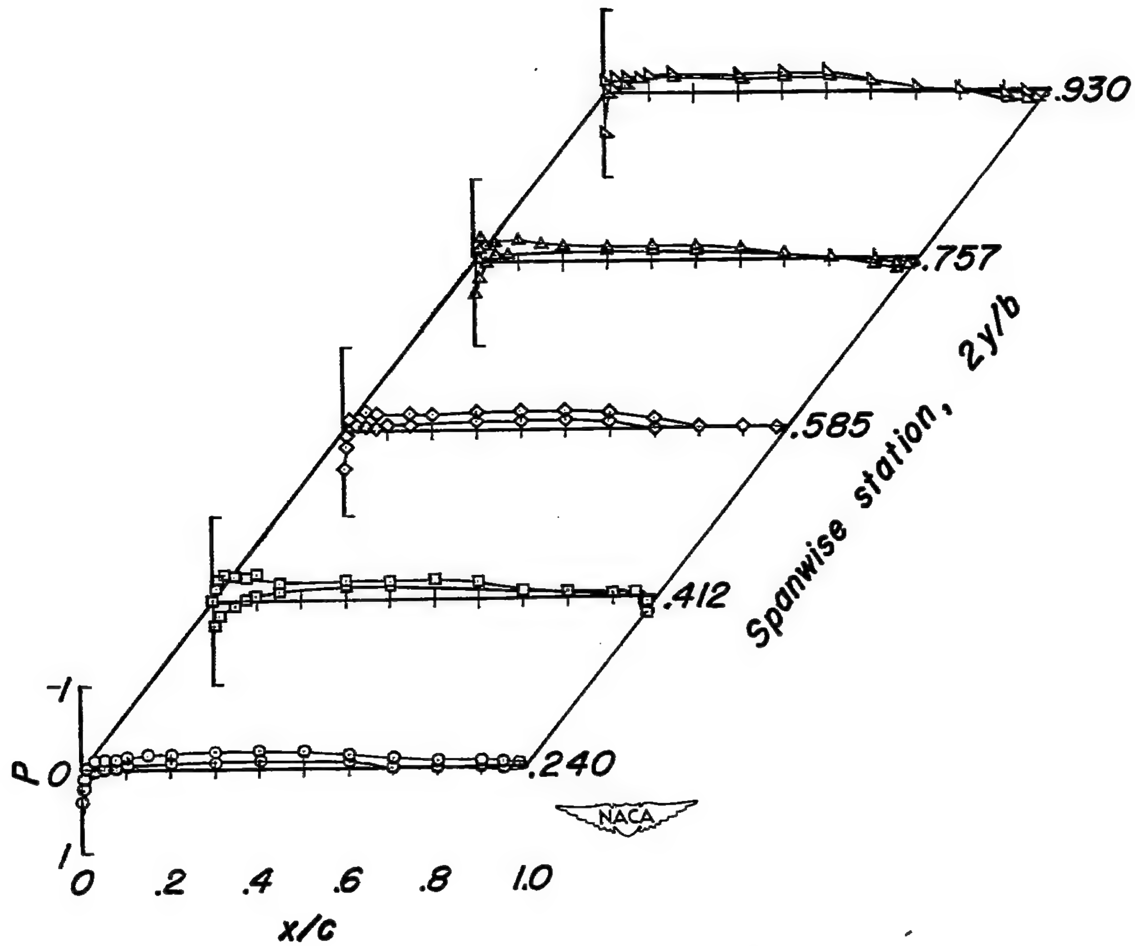
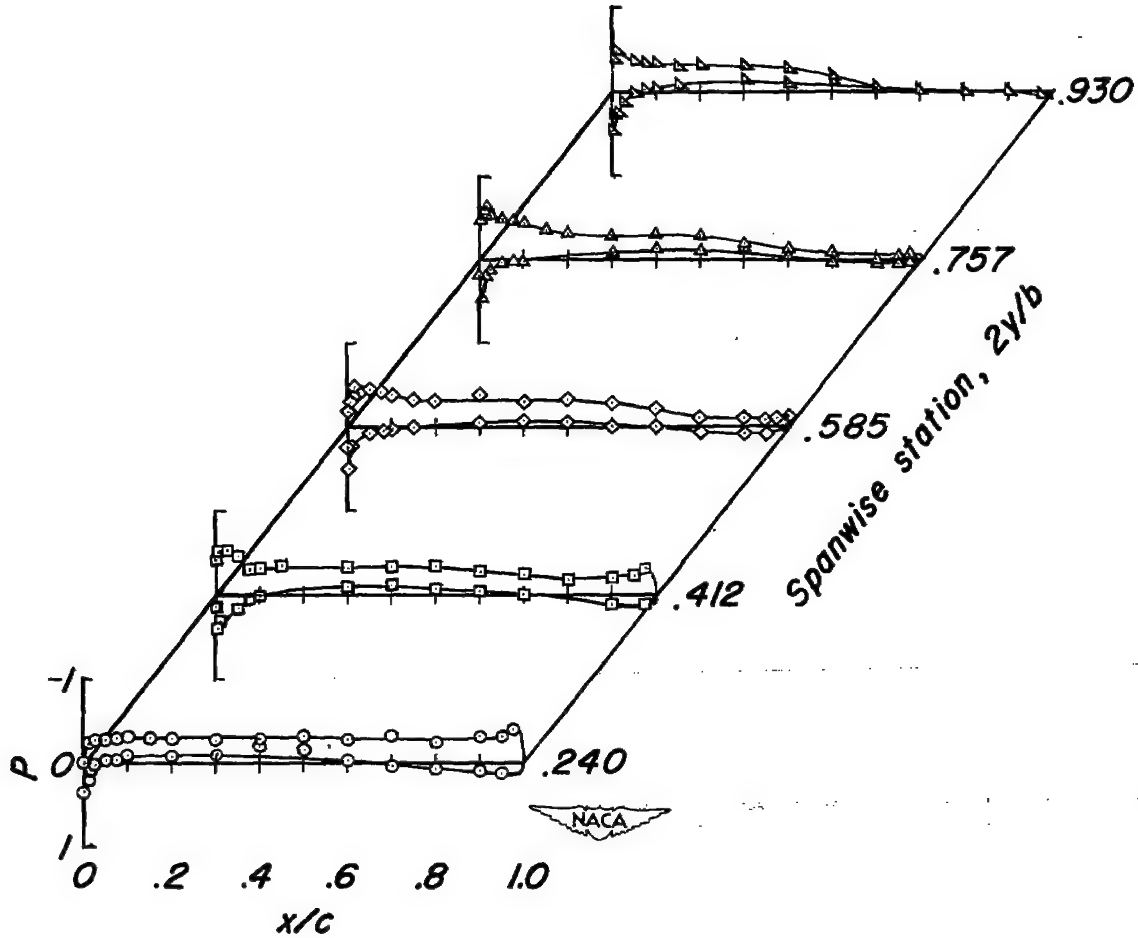


Figure 7.- Variation of flow, pitching-moment, and suction pressure coefficients with lift coefficient; slot, $s/c' = 0.01$, $d/c' = 0.013$.



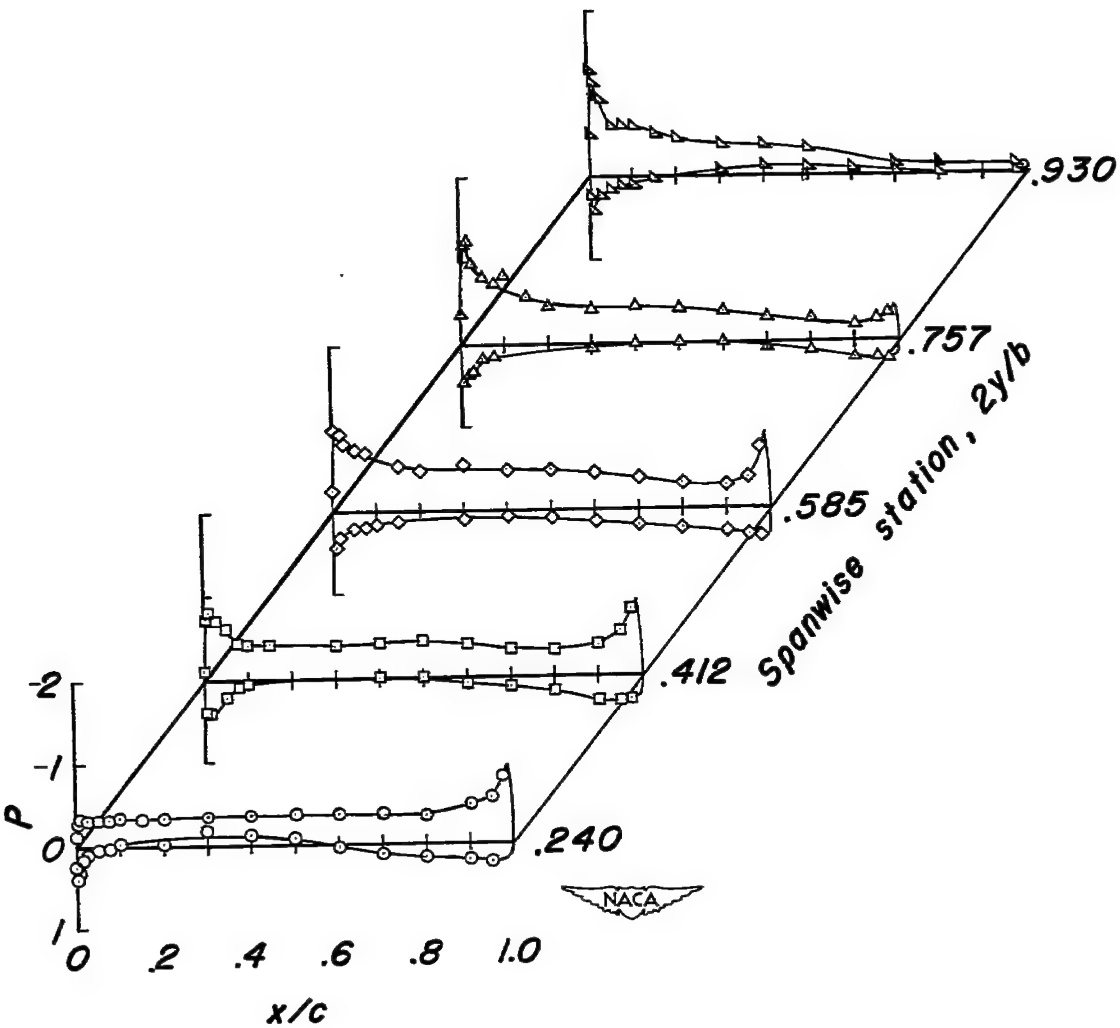
(a) $C_{Q_{TE}} = 0$, $C_L = 0.05$

Figure 8.- Chordwise pressure distributions on 45° sweptback wing with circulation control; slot, $s/c' = 0.01$, $d/c' = 0.013$; $\alpha_u = 0$.



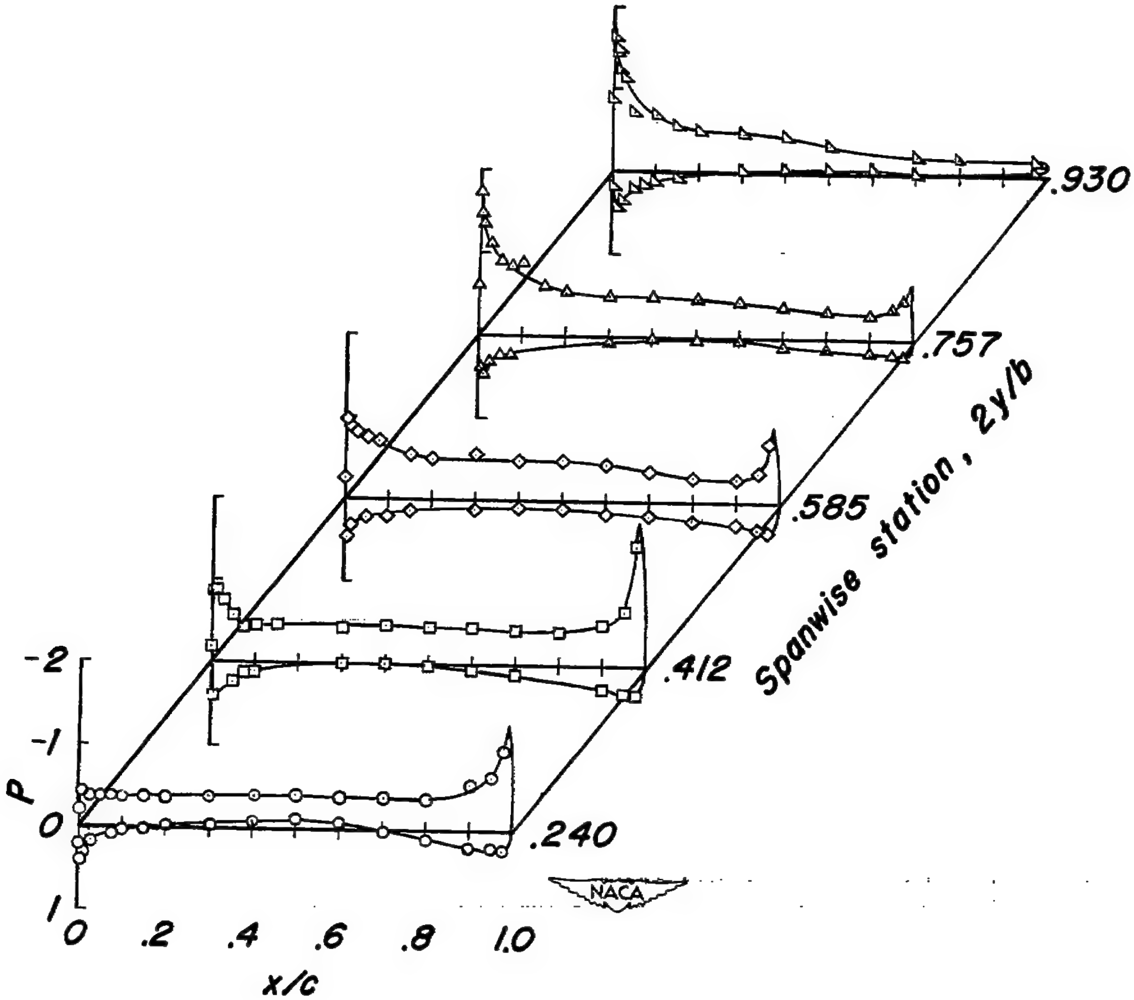
(b) $C_{Q_{TE}} = 0.0026$, $C_L = 0.23$

Figure 8.- Continued.



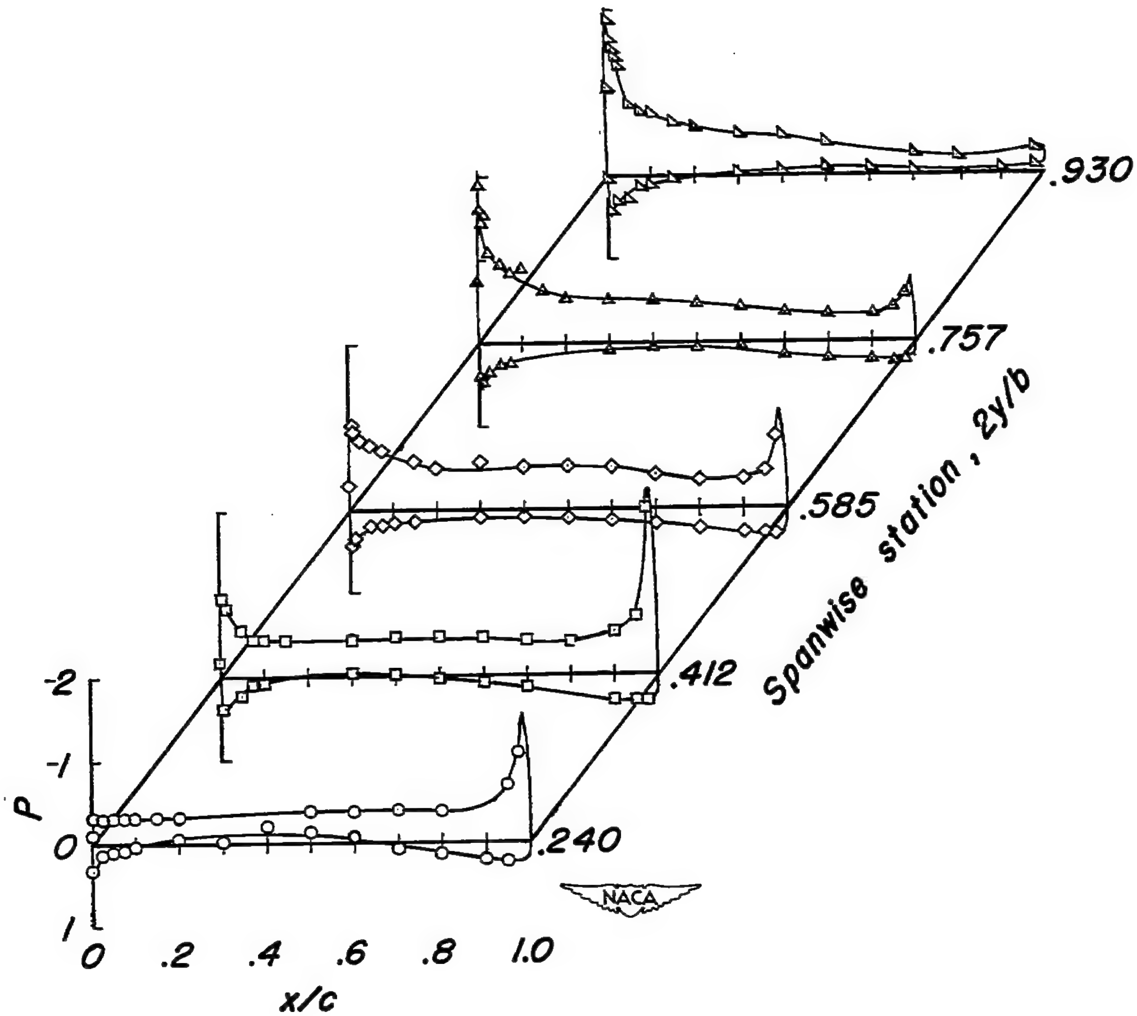
(c) $C_{Q_{TE}} = 0.0064$, $C_L = 0.43$

Figure 8.- Continued.



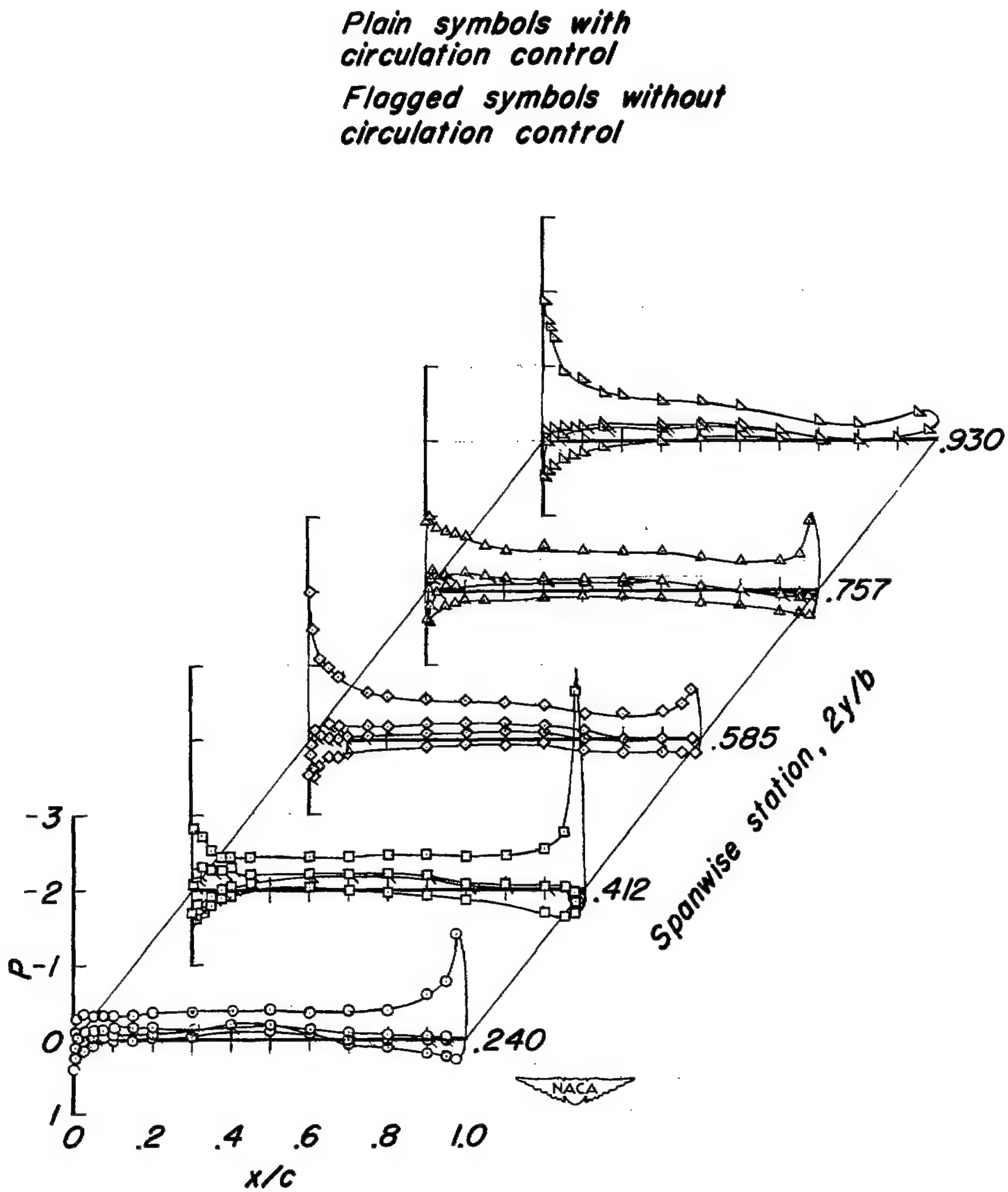
(d) $C_{Q_{TE}} = 0.0099$, $C_L = 0.48$

Figure 8.- Continued.



(e) $C_{Q_{TE}} = 0.0136$, $C_L = 0.49$

Figure 8.- Continued.



(f) $C_{Q_{TE}} = 0.0158$, $C_L = 0.5$

Figure 8- Concluded.

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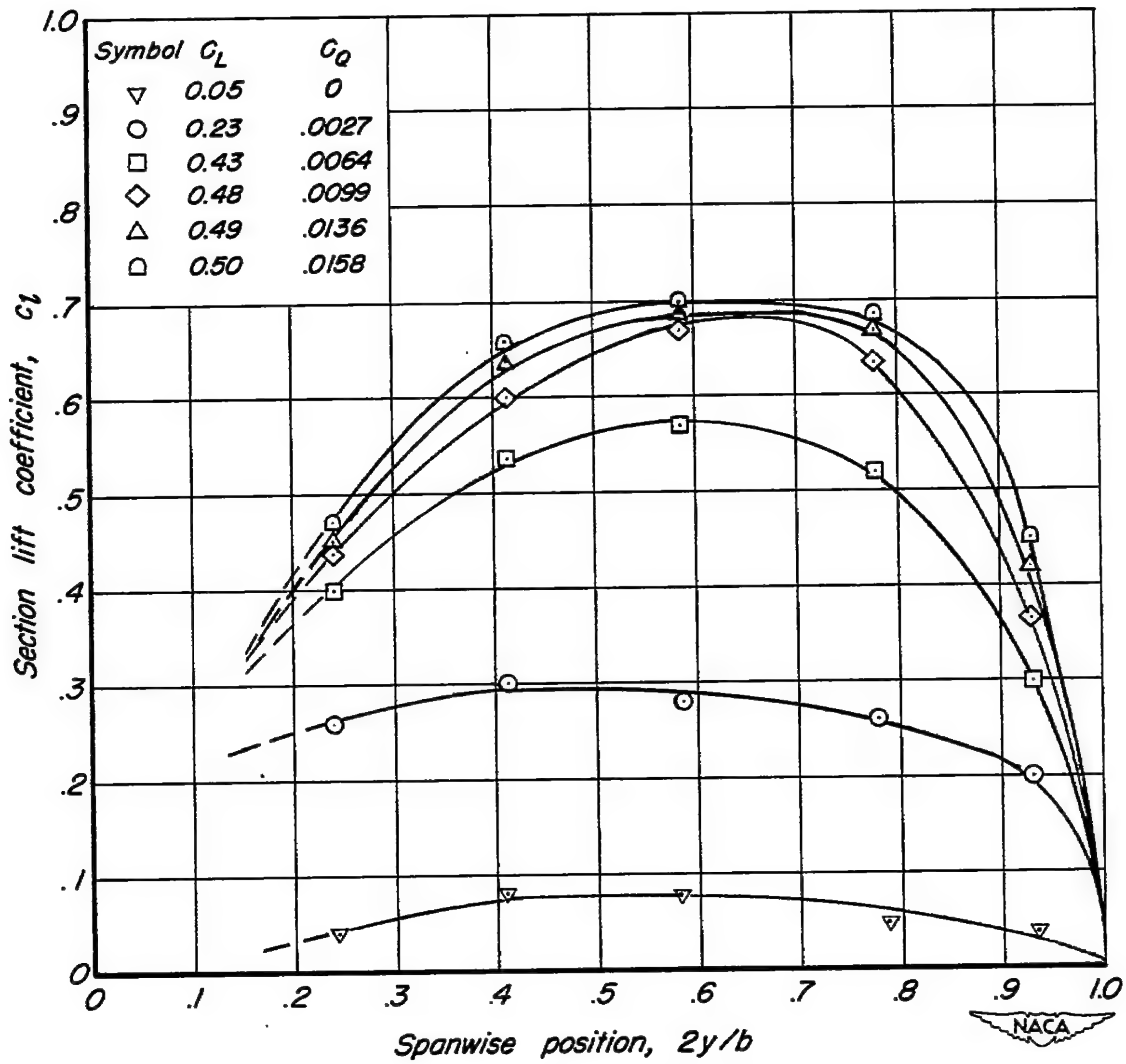

Figure 9.- Variation of streamwise section lift coefficient across wing span for several flow coefficients; α_u = 0; slot, s/c' = 0.01, d/c' = 0.013.

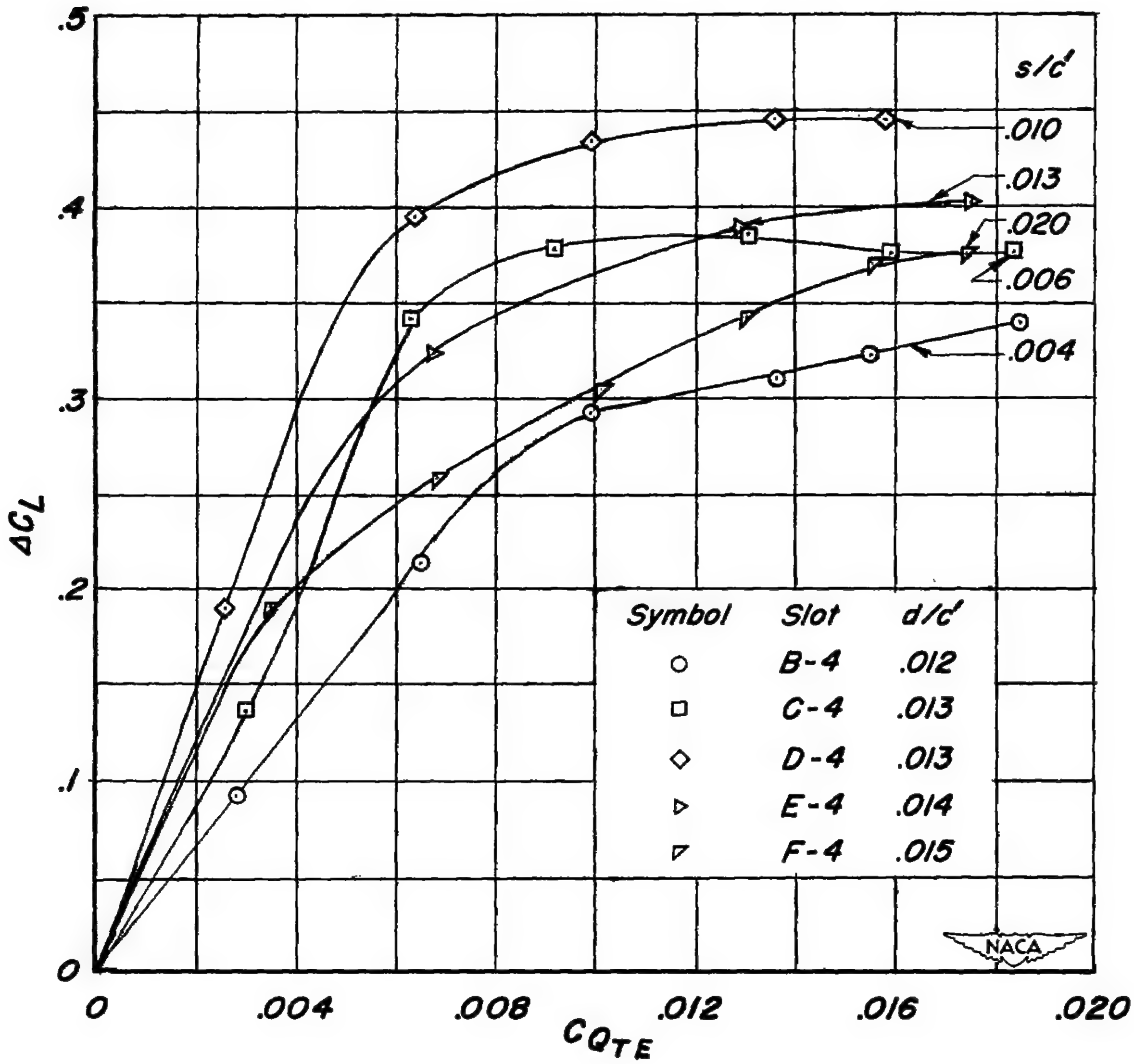

Figure 10.- Variation of increment of lift due to circulation control with flow coefficient for various chordwise extents of slot; $\alpha_u = 0^{\circ}$.

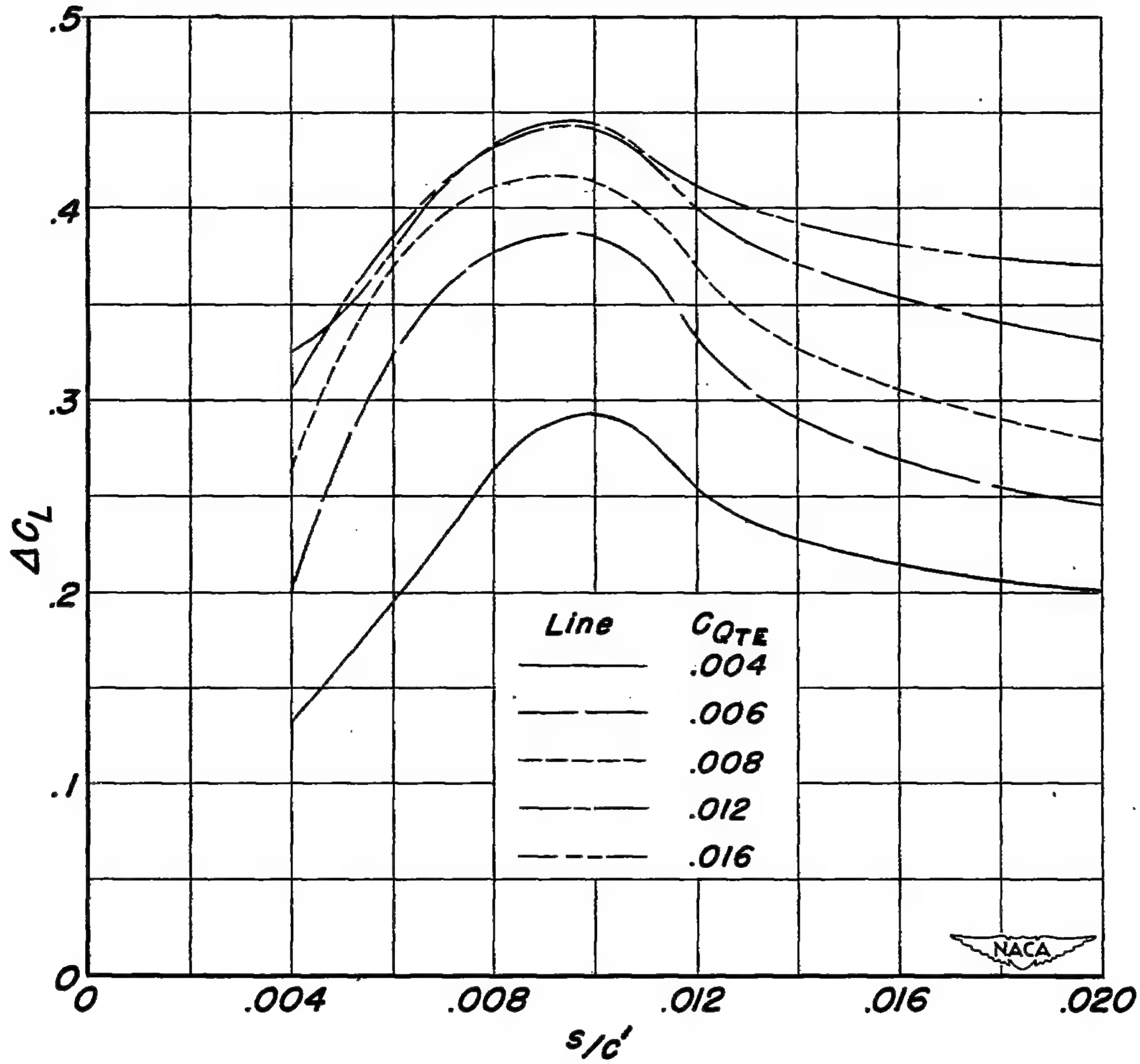

Figure 11.- Variation of lift increment due to circulation control with chordwise extent of slot; slot depth $d/c' \cong 0.013$, $\alpha_u = 0^{\circ}$.

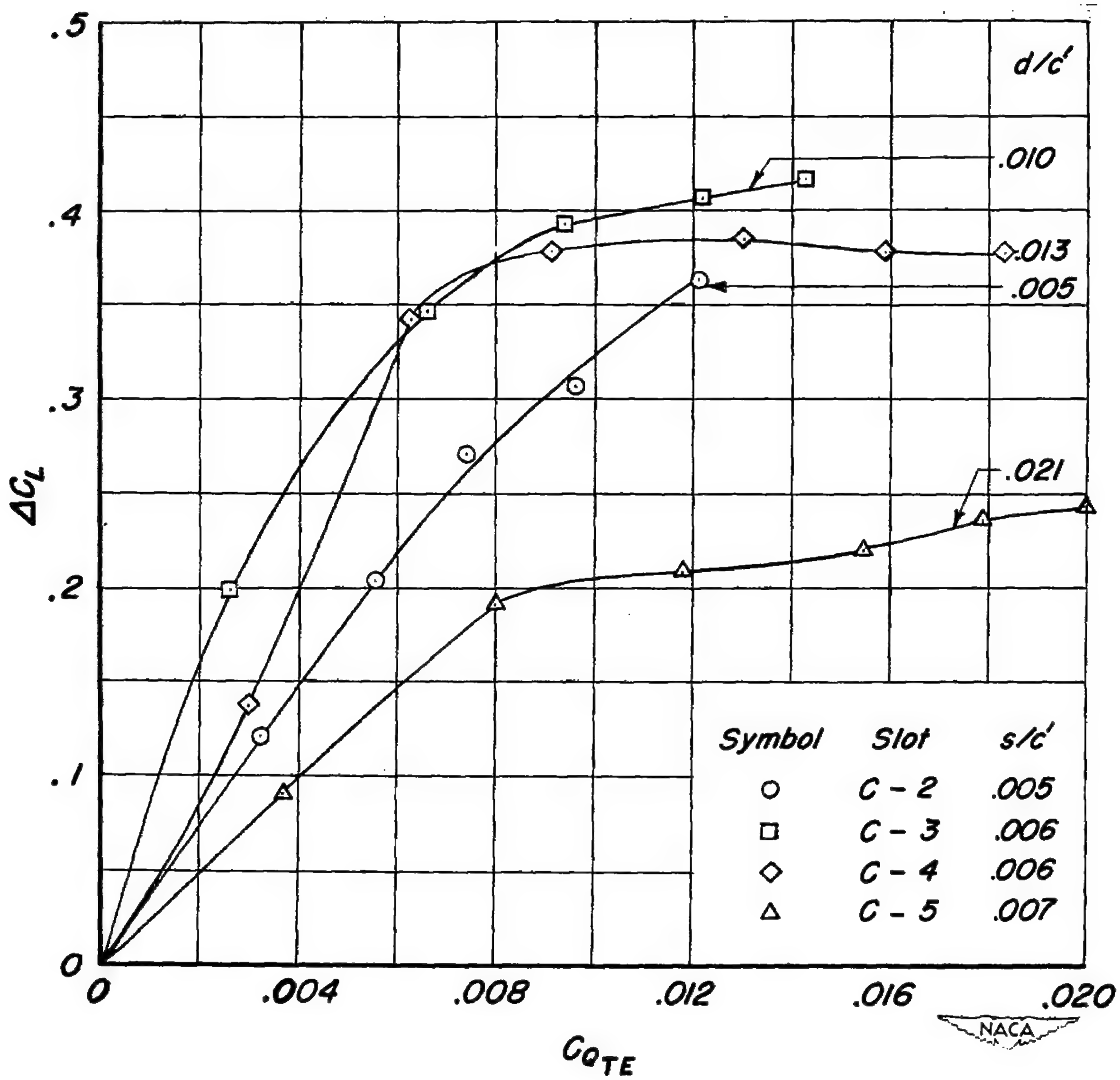

Figure 12.- Variation of lift increment due to circulation control with flow coefficient for various slot depths; $s/c' \cong 0.006$, $\alpha_u = 0^\circ$.

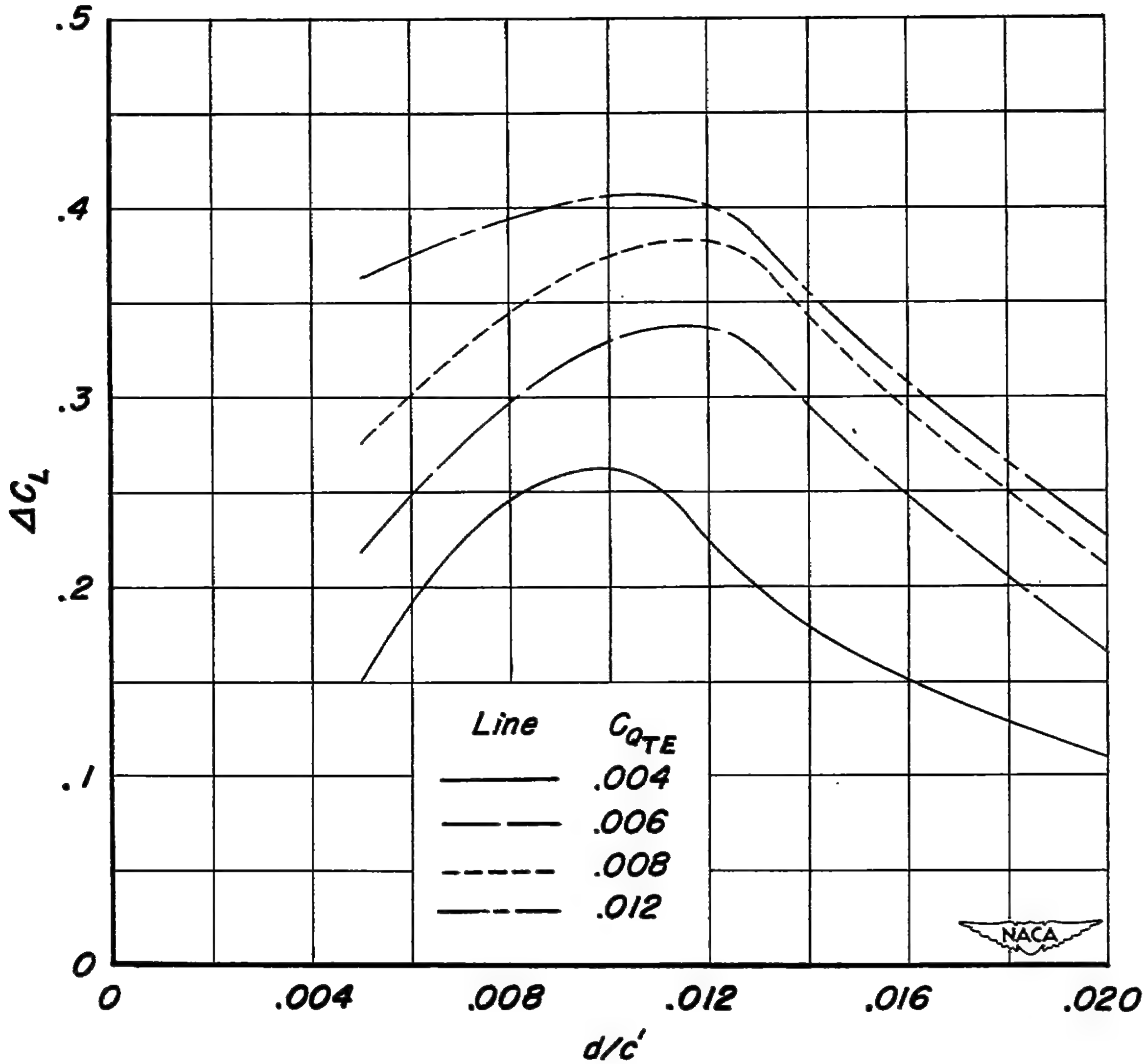

Figure 13.- Variation of lift increment due to circulation control with slot depth; slot extent, s/c' ≅ 0.006; $\alpha_u = 0^{\circ}$.

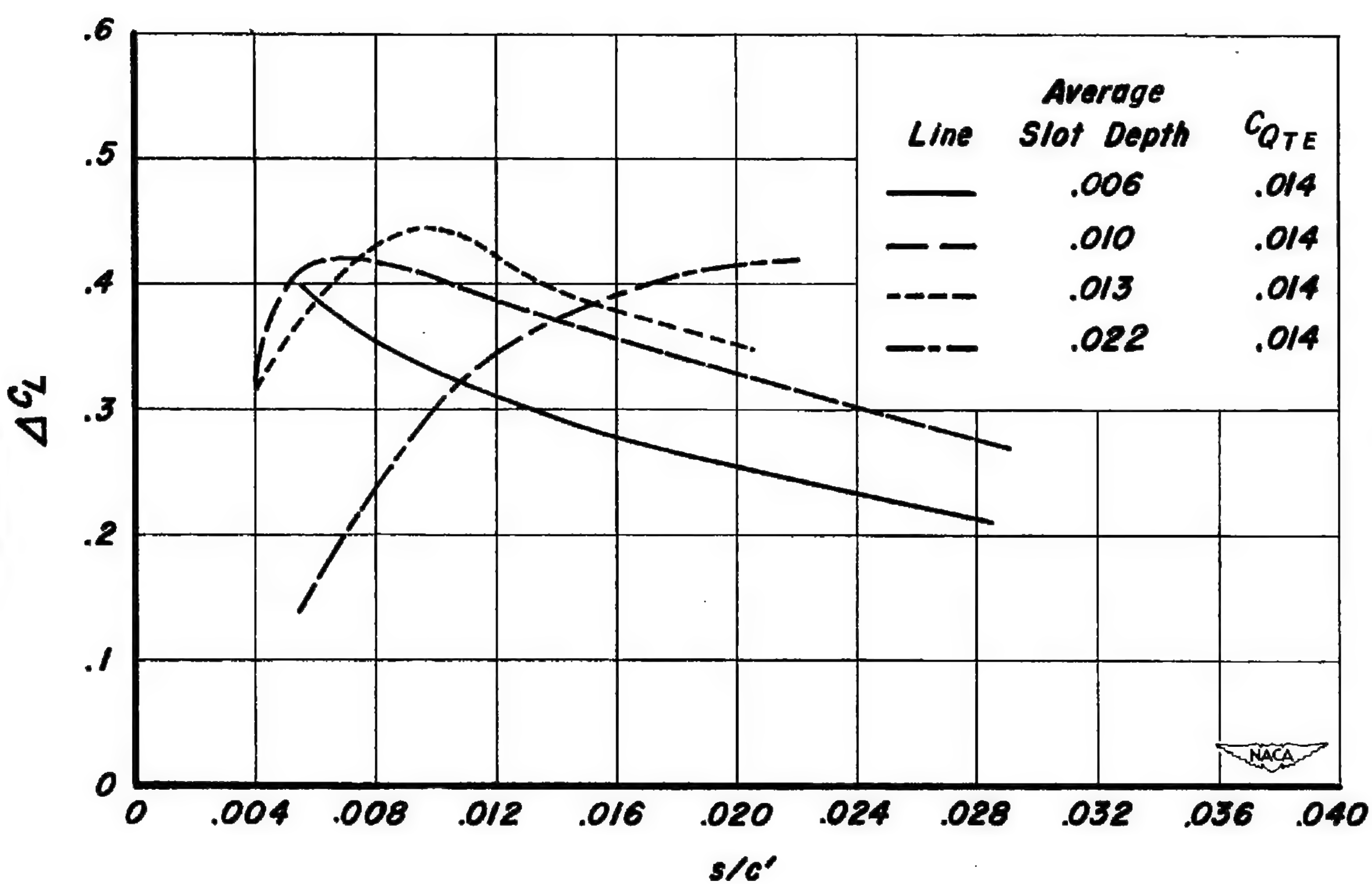

Figure 14.- Variation of lift increment due to circulation control with chordwise extent of slot for various depths; $\alpha_u = 0^{\circ}$.

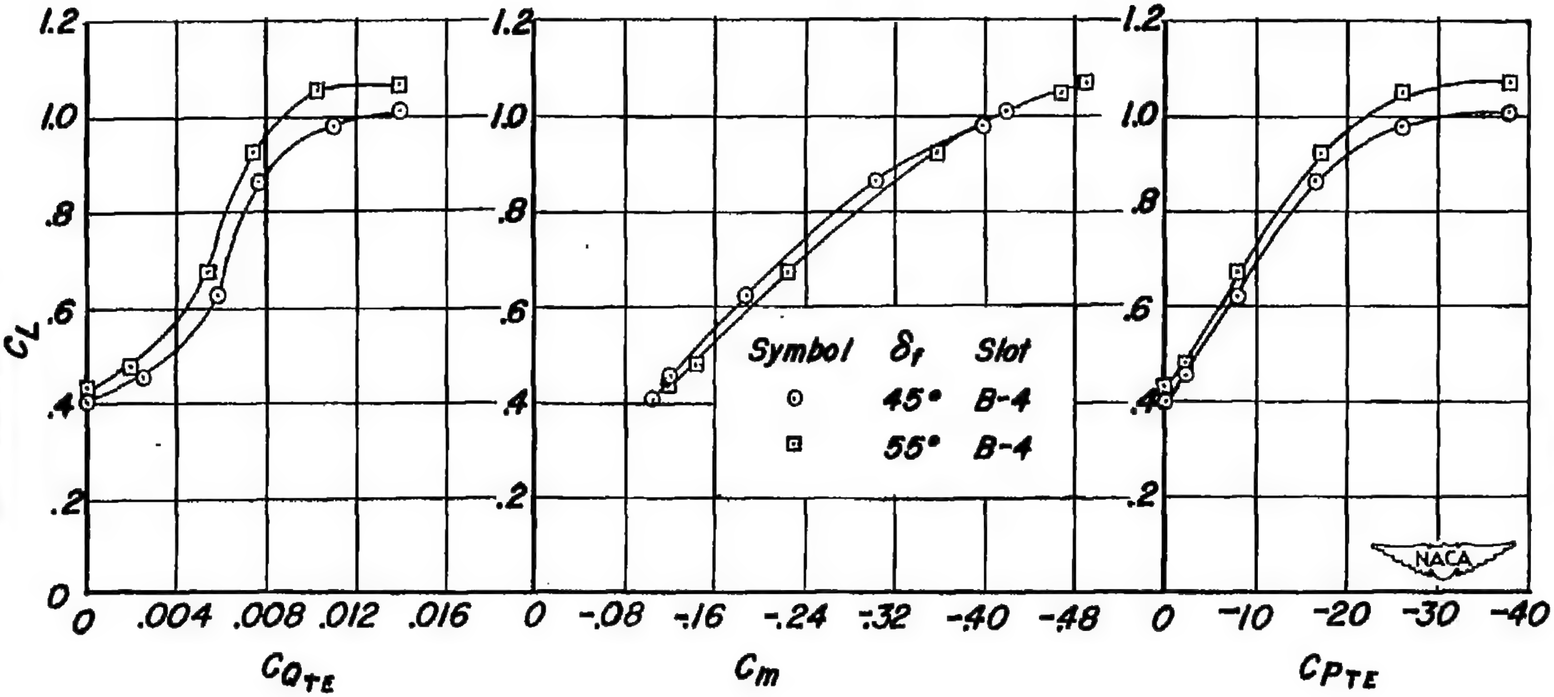

Figure 15.- Variation of flow, pitching-moment, and suction pressure coefficients with lift coefficient; slot, $s/c' = 0.004$, $d/c' = 0.012$; $\alpha_u = 0^\circ$; $\delta_f = 45^\circ$ and 55°.

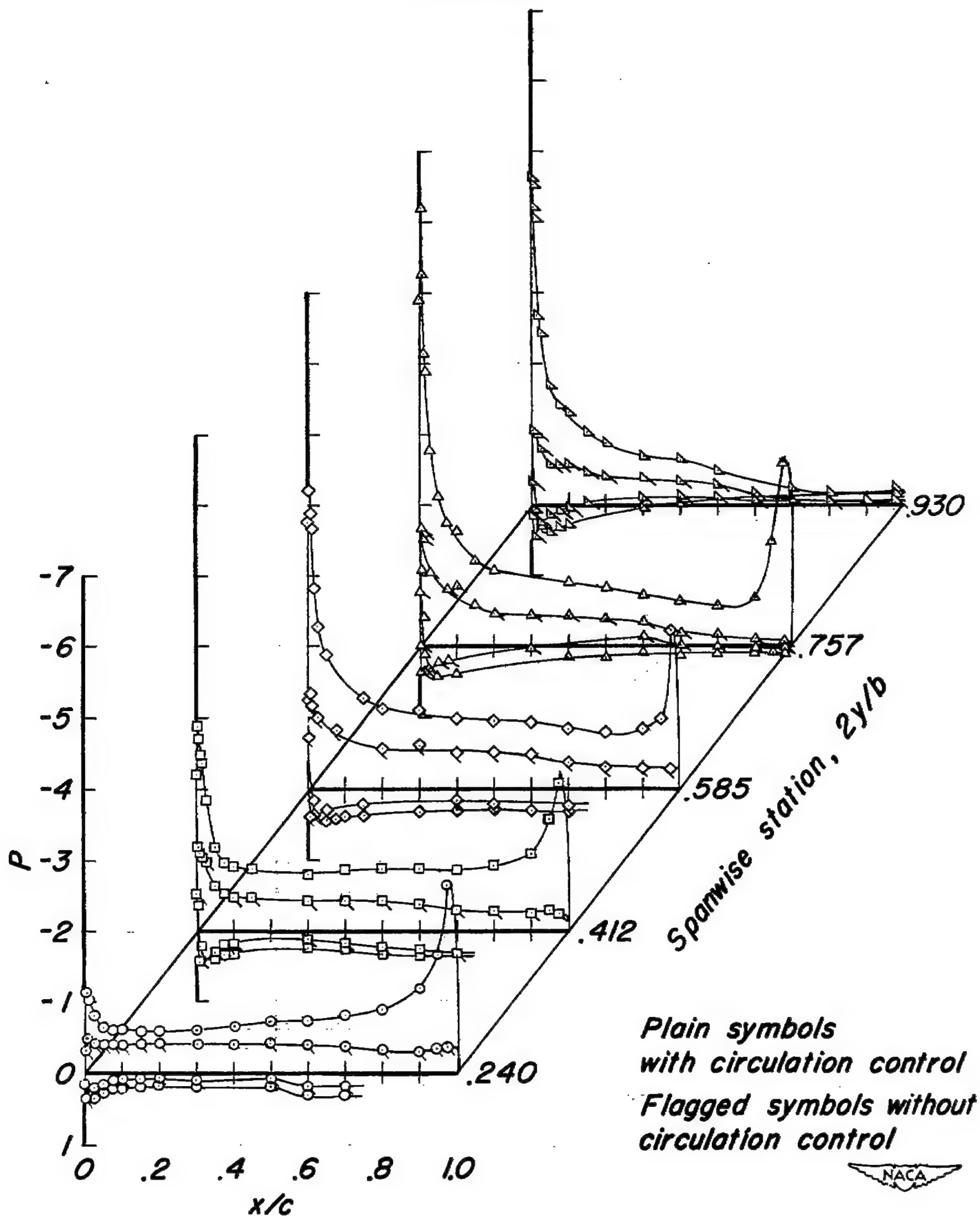

Figure 16.- Chordwise pressure distribution on wing with circulation control; slot, $s/c' = 0.004$, $d/c' = 0.012$; $\delta_f = 45^\circ$; $\alpha_u = 0^\circ$; $c_Q = 0.0138$.

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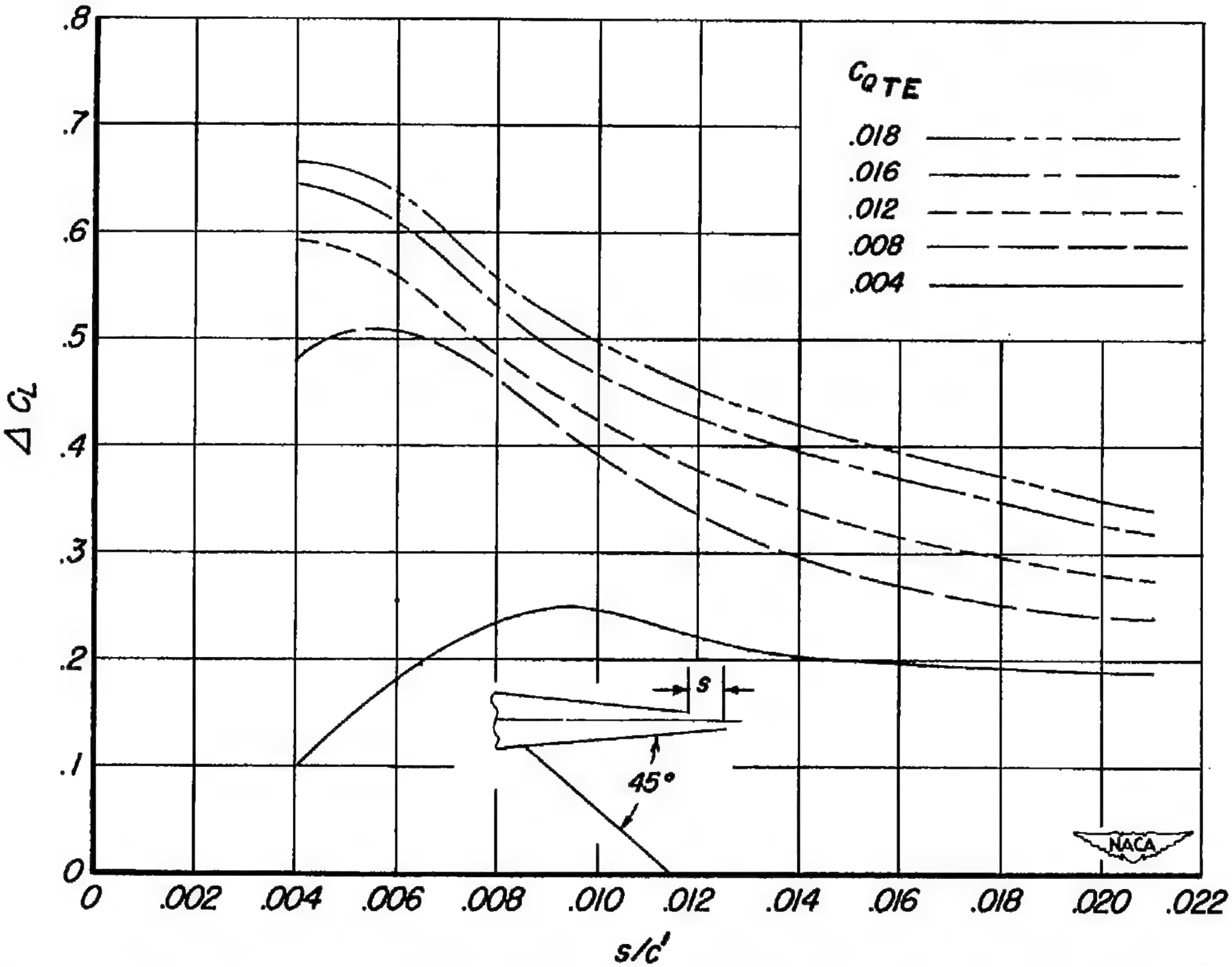

Figure 17.- Variation of lift increment due to circulation control with chordwise extent of slot; $\delta_f = 45^\circ$; slot, $d/c' \cong 0.013^\circ$, $\alpha_u = 0^\circ$.

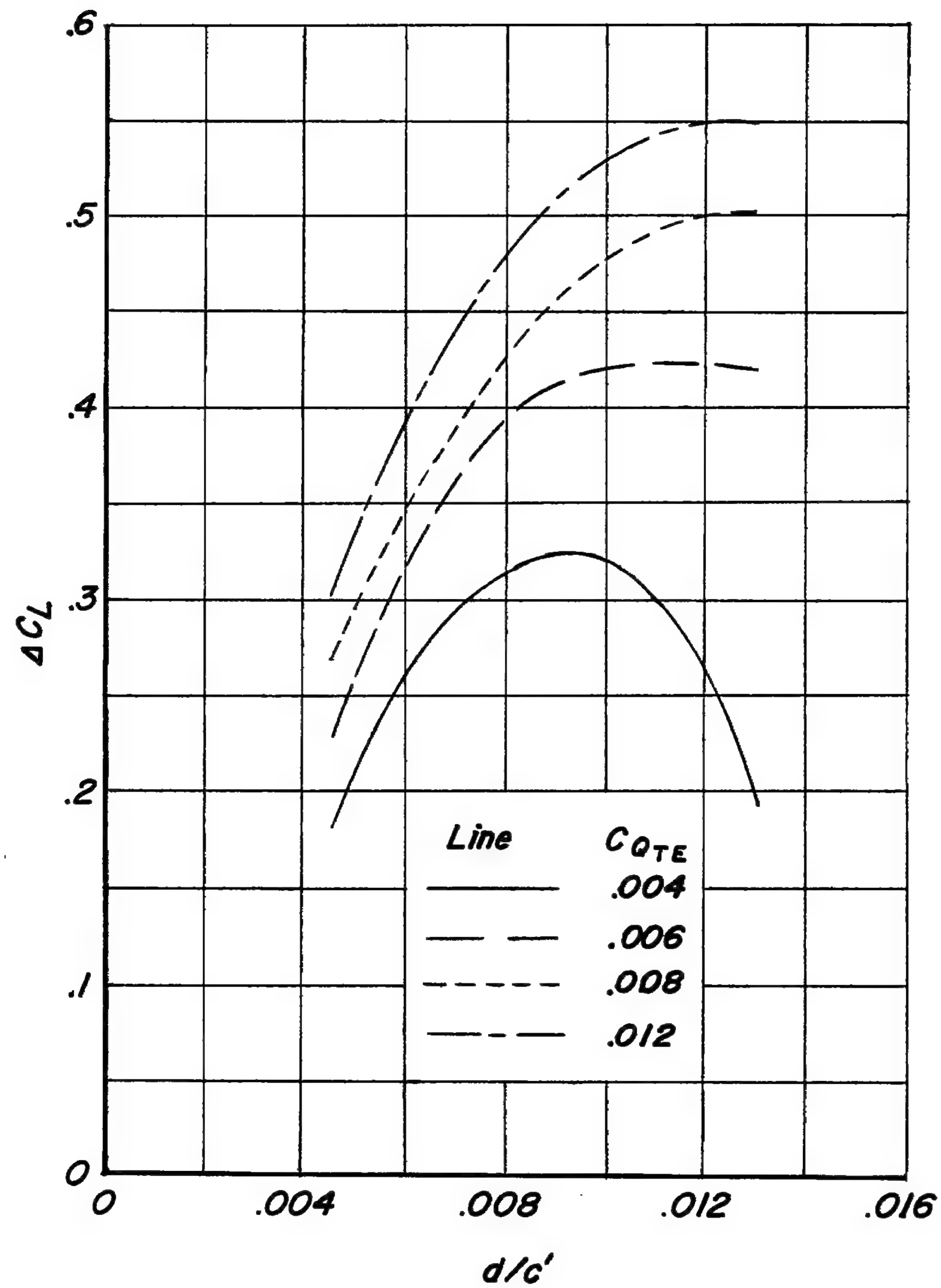

Figure 18.- Variation of lift increment due to circulation control with slot depth; slot extent, $s/c' \cong 0.006$; $\delta_f = 45^\circ$; $\alpha_u = 0^\circ$.

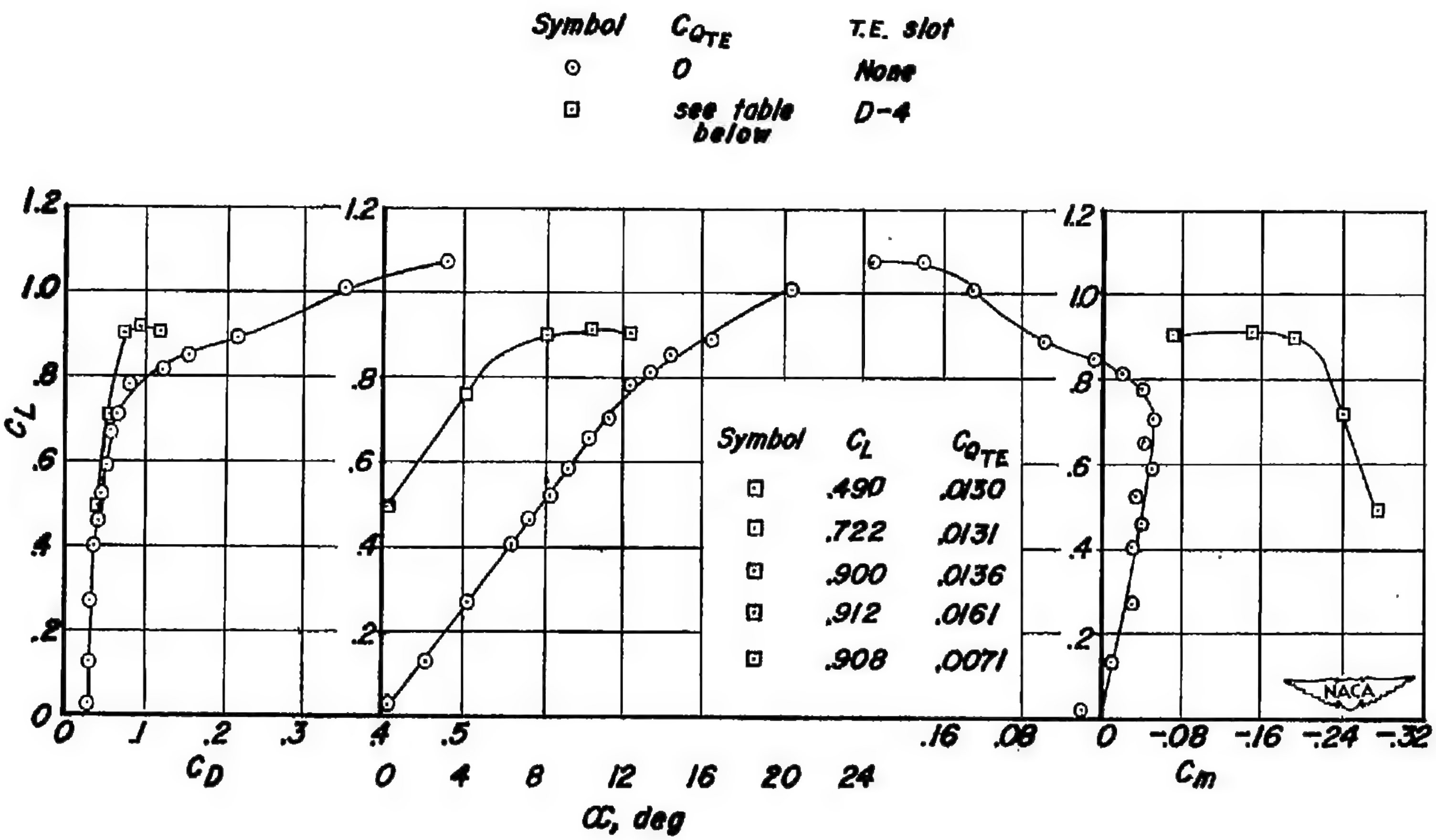

Figure 19.- Longitudinal characteristics of wing with and without circulation control; slot, s/c' = 0.01, d/c' = 0.013.

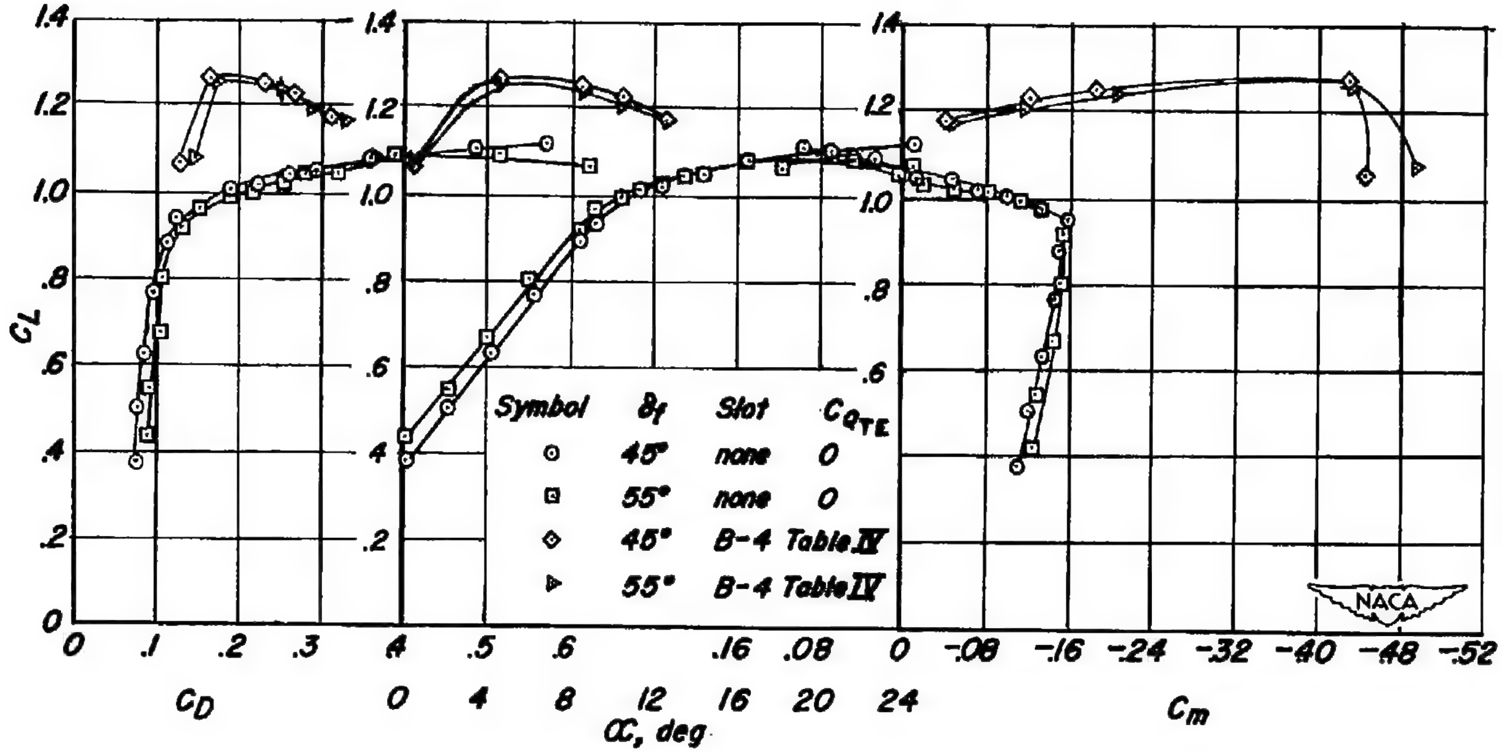

Figure 20.- Longitudinal characteristics of wing with and without circulation control; s/c' = 0.004, d/c' = 0.012.

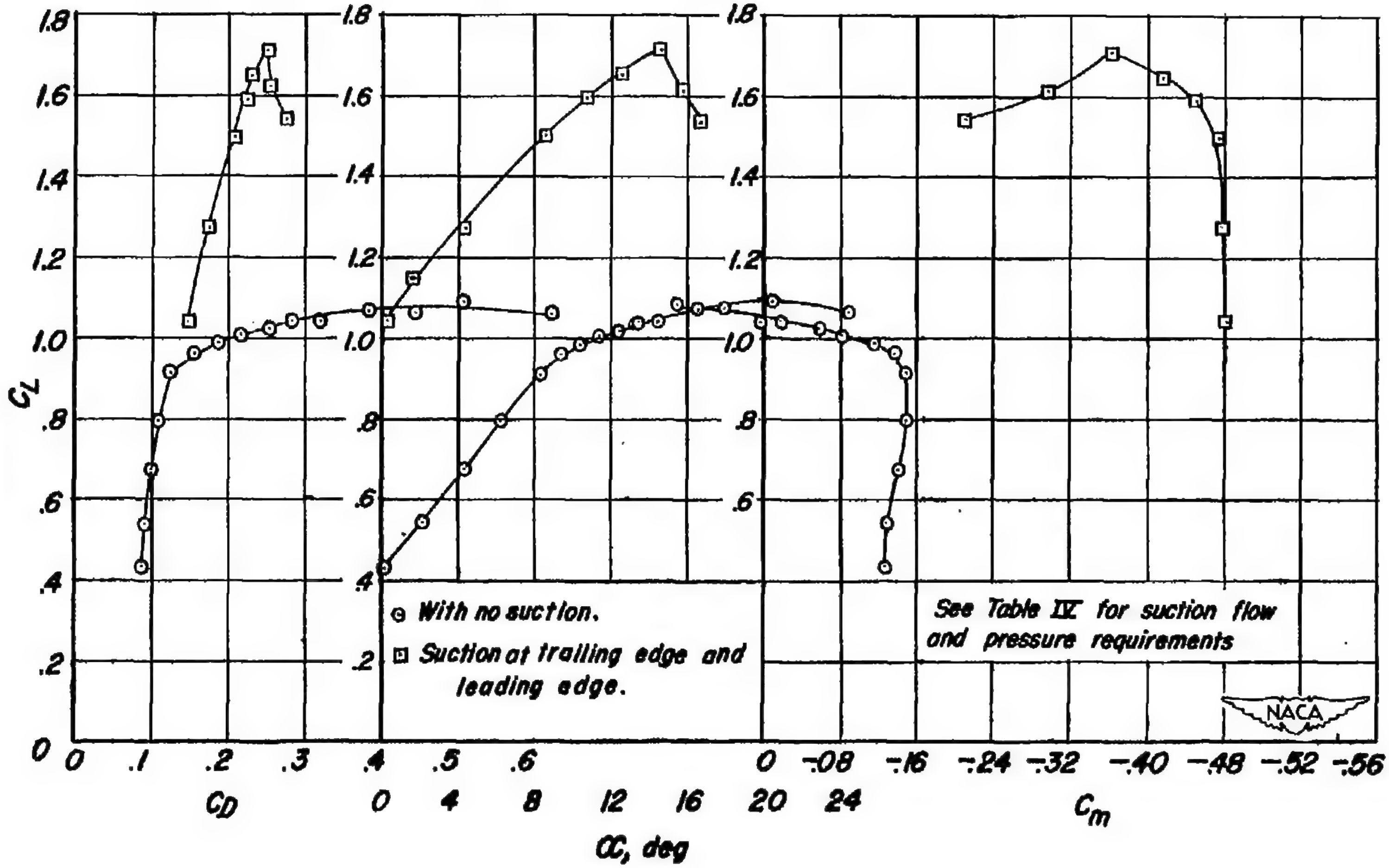

Figure 21.- Longitudinal characteristics of the wing with circulation control; area suction applied at wing leading edge; trailing-edge slot B-4, $s/c' = 0.004$, $d/c' \cong 0.012$; $\delta_f = 55^\circ$.

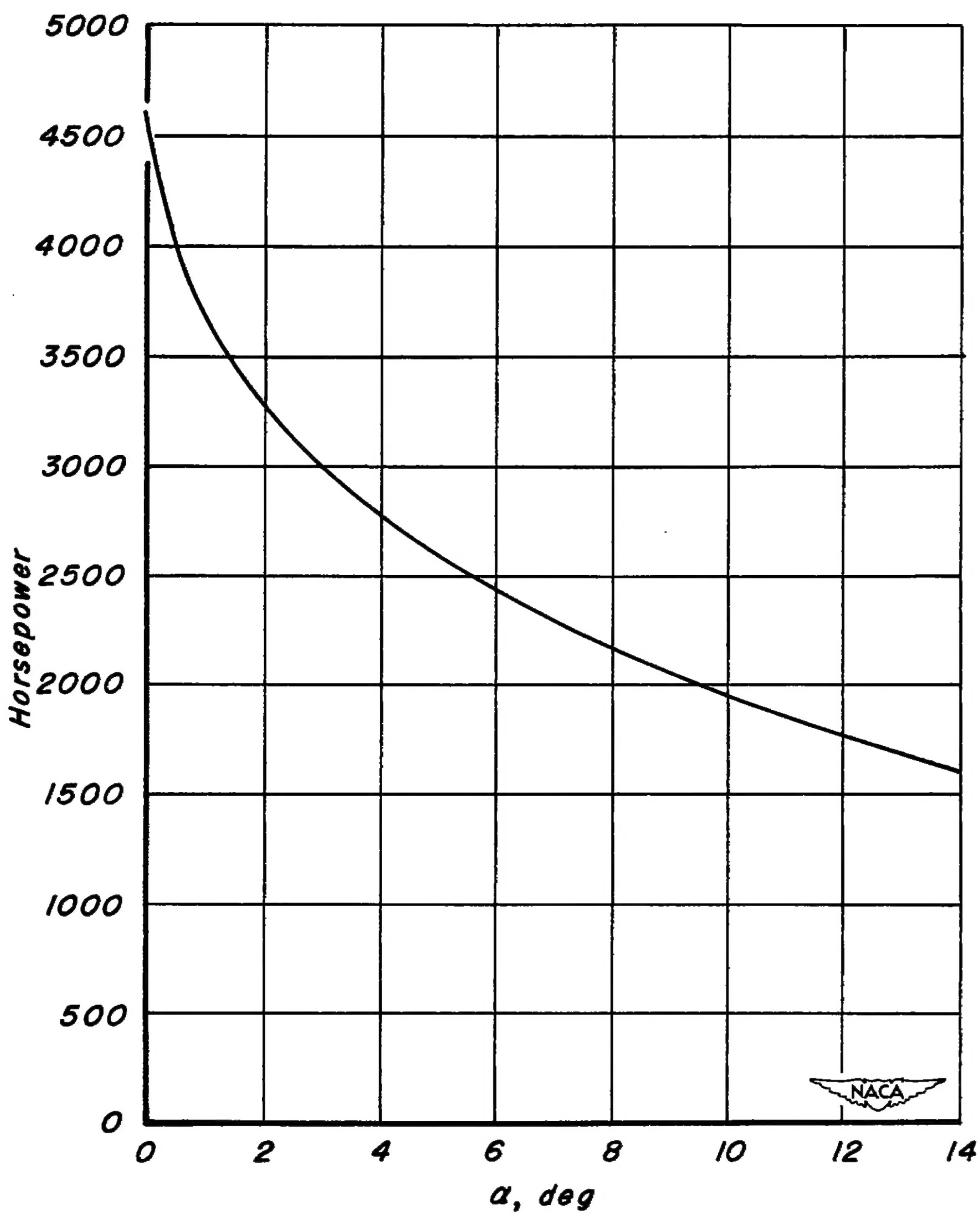

Figure 22.- Variation of calculated horsepower requirements with angle of attack for circulation control for 45° sweptback wing; simulated airplane wing loading of 40 pounds per square foot and wing area 400 square feet; $\delta_f = 55^\circ$.

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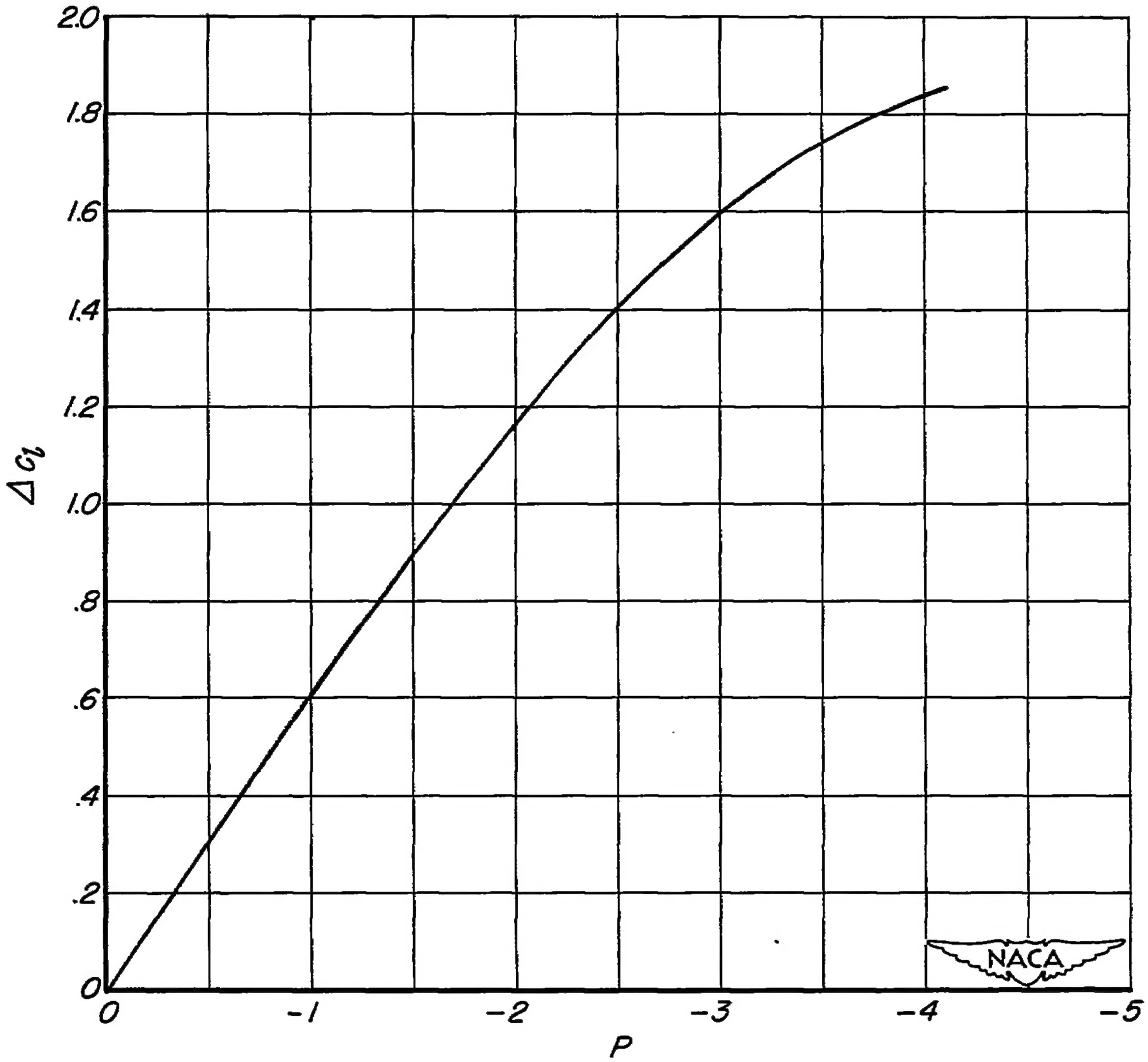

Figure 23.- Variation of section lift increment due to circulation control with surface pressure coefficient at 97.5-percent chord obtained from two-dimensional section data.

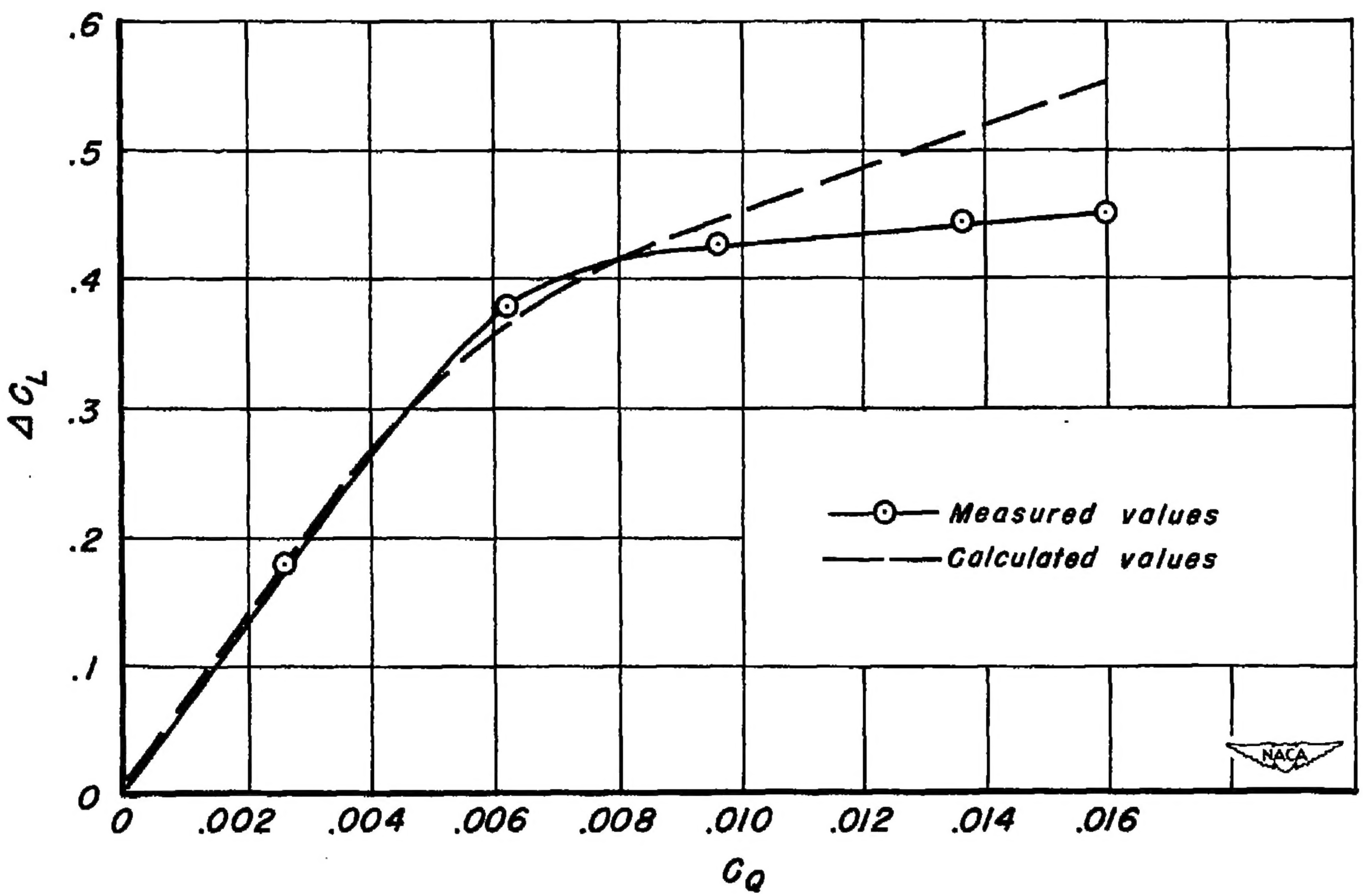

Figure 24.- Comparison of calculated values of wing lift coefficients and measured values of lift coefficient for the range of flow coefficients tested.

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